The performance of improved H-modes at ASDEX Upgrade and projection to ITER

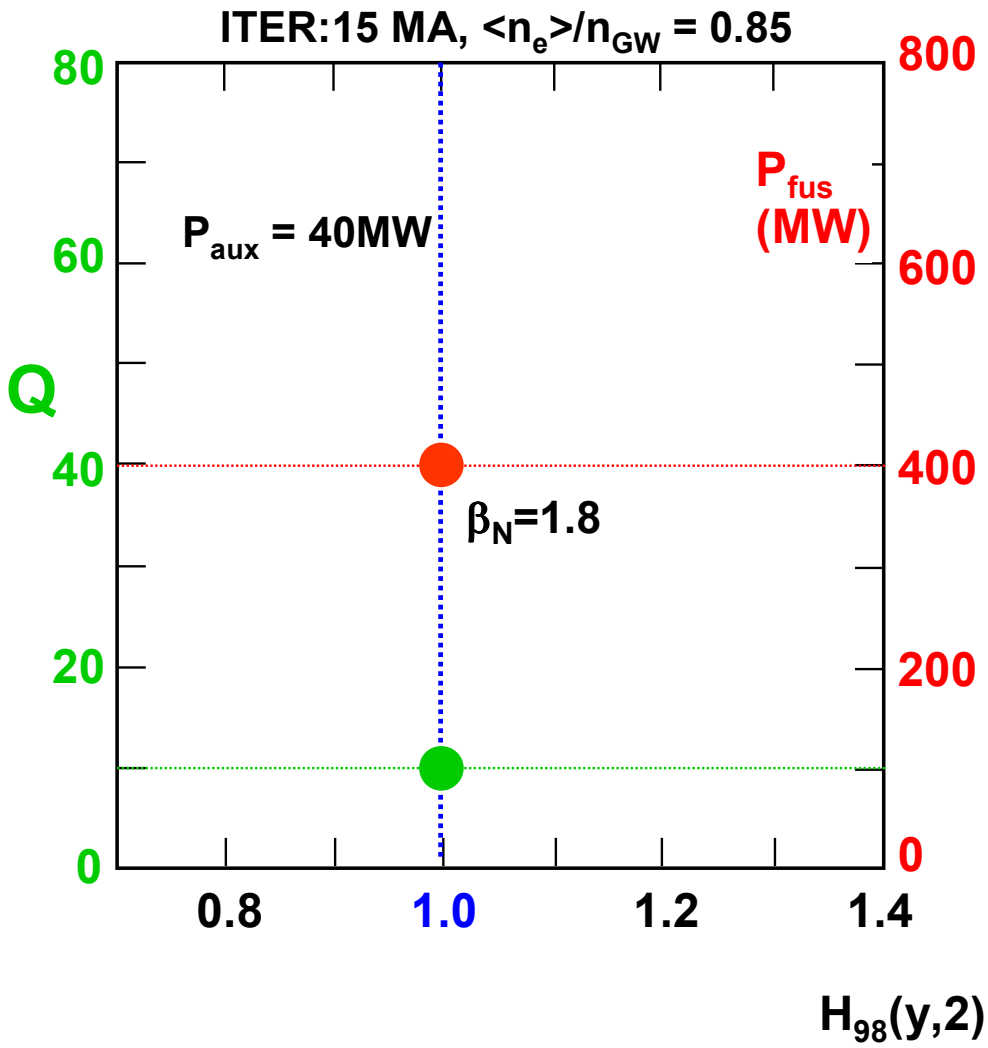
George Sips

MPI für Plasmaphysik, EURATOM-Association, D-85748, Germany

G. Tardini[1], C. Forest[2], O. Gruber[1], P. Mc Carthy[3], A. Gude[1], L.D. Horton[1], V. Igochine[1], O. Kardaun[1], C.F. Maggi[1], M. Maraschek[1], V. Mertens[1], R. Neu[1], A. Peeters[1], G. V. Pereverzev[1], A. Stäbler[1], J. Stober[1], W. Suttrop[1] and the ASDEX Upgrade Team.

[1] Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748, Germany.
[2]The University of Wisconsin, Madison, USA.
[3]Dep. of Physics, University College Cork, Association EURATOM-DCU, Cork, Ireland.

Motivation: ITER performance



ITER primary goal:
Q=10, P_{fus}~400MW.

Energy confinement:
IPB98(y,2) scaling expression.

→ ITER size, 15MA/5.3T,
$P_{aux} \leq 73$ MW, $\langle n_e \rangle = 0.85$,….

Mukhovatov V. et al Nucl. Fusion 43 (2003) 942

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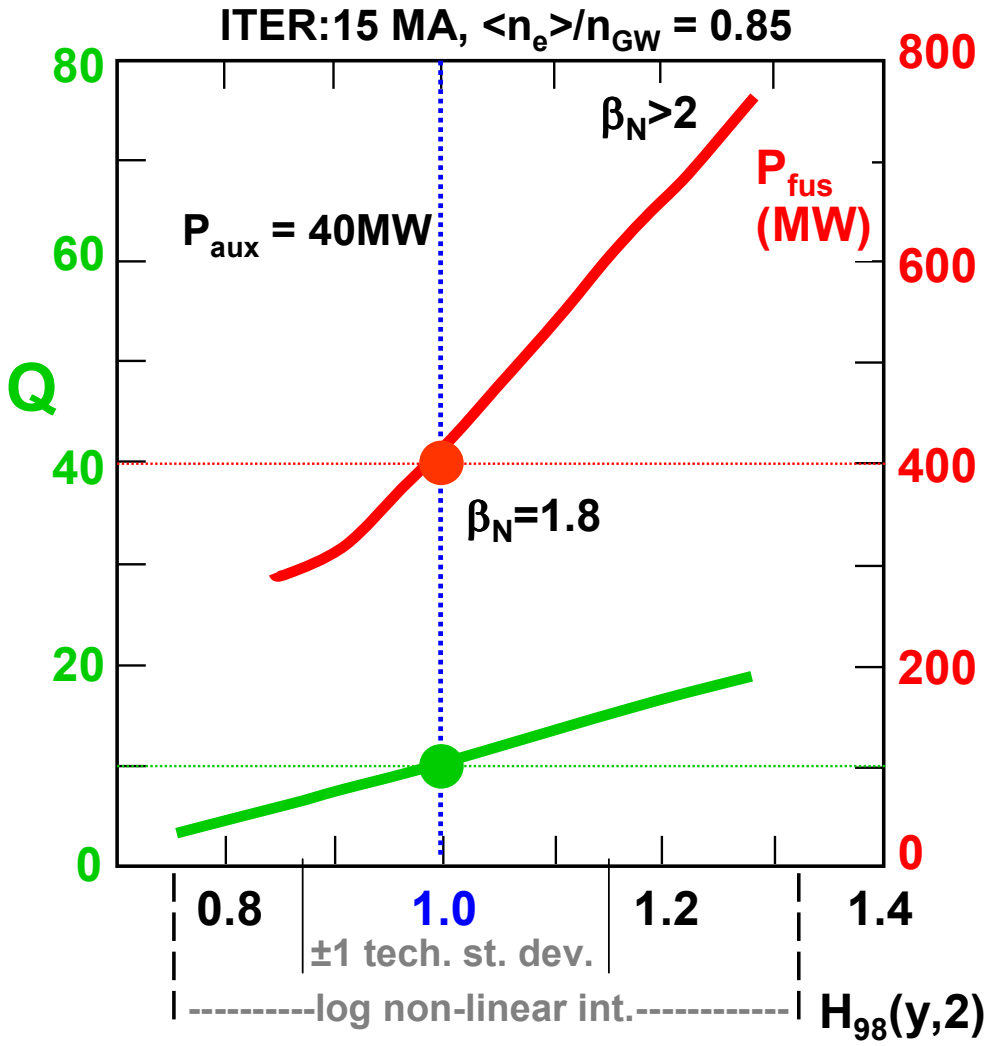


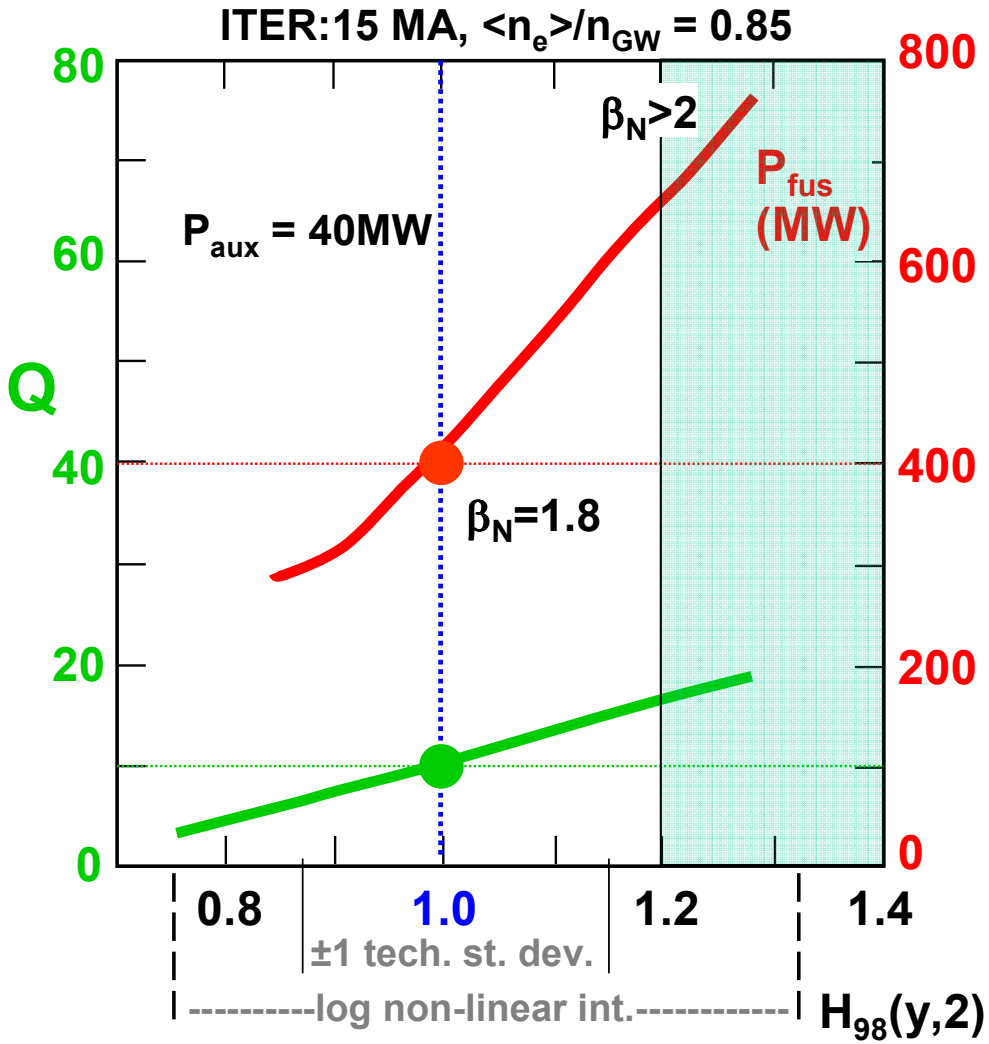
Integrated simulation codes:→ 'envelope' of performance.

- Strong dependence, of Q and P_{fus} with $H_{98}(y,2)$.

Significant increase in ITER performance for 'small' increase in energy confinement.

Mukhovatov V. et al Nucl. Fusion 43 (2003) 942

Motivation: ITER performance



Integrated simulation codes:→ 'envelope' of performance.

- Strong dependence, of Q and P_{fus} with $H_{98}(y,2)$.

Significant increase in ITER performance for 'small' increase in energy confinement.

$H_{98}(y,2) > 1$, and $\beta_N > 2$:

- Higher performance at 15 MA.
- Long pulse operation, I_p=11 to 14 MA, with Q=5-10 (Hybrid).
- DEMO: $H_{98}(y,2) \geq 1.2$, $\beta_N \geq 3.5$.

Mukhovatov V. et al Nucl. Fusion 43 (2003) 942

Motivation → Outline

- **ASDEX Upgrade:**

  Improved H-modes ($H_{98}(y,2) > 1$, and $\beta_N > 2$).

- **Operational range:**

  - wide range in density, T_{i0}/T_{e0} and ν^*.

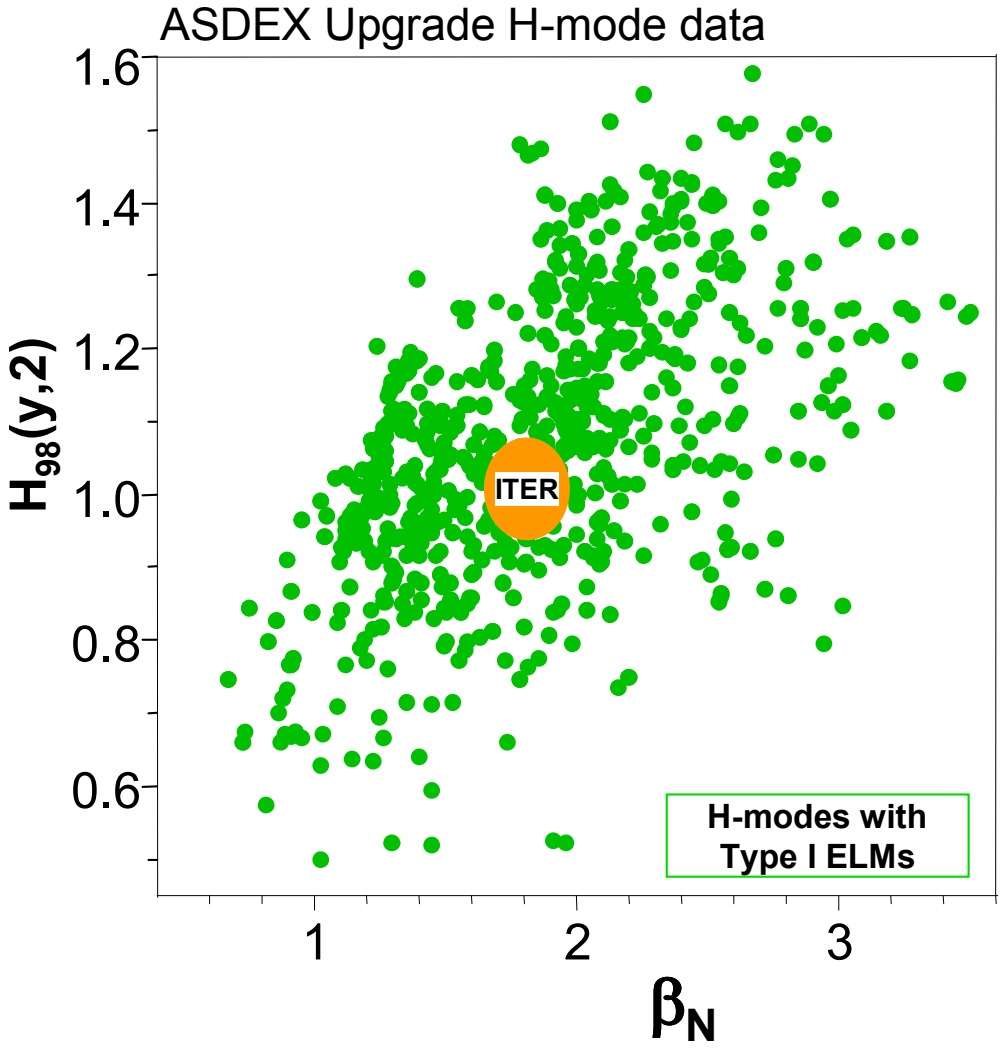
  - at $q_{95} \rightarrow 3.1$.

  - high beta: Limits and control of NTMs.

- **Scaling to ITER using experimental data.**

- **Conclusions.**

ASDEX Upgrade: H-mode data



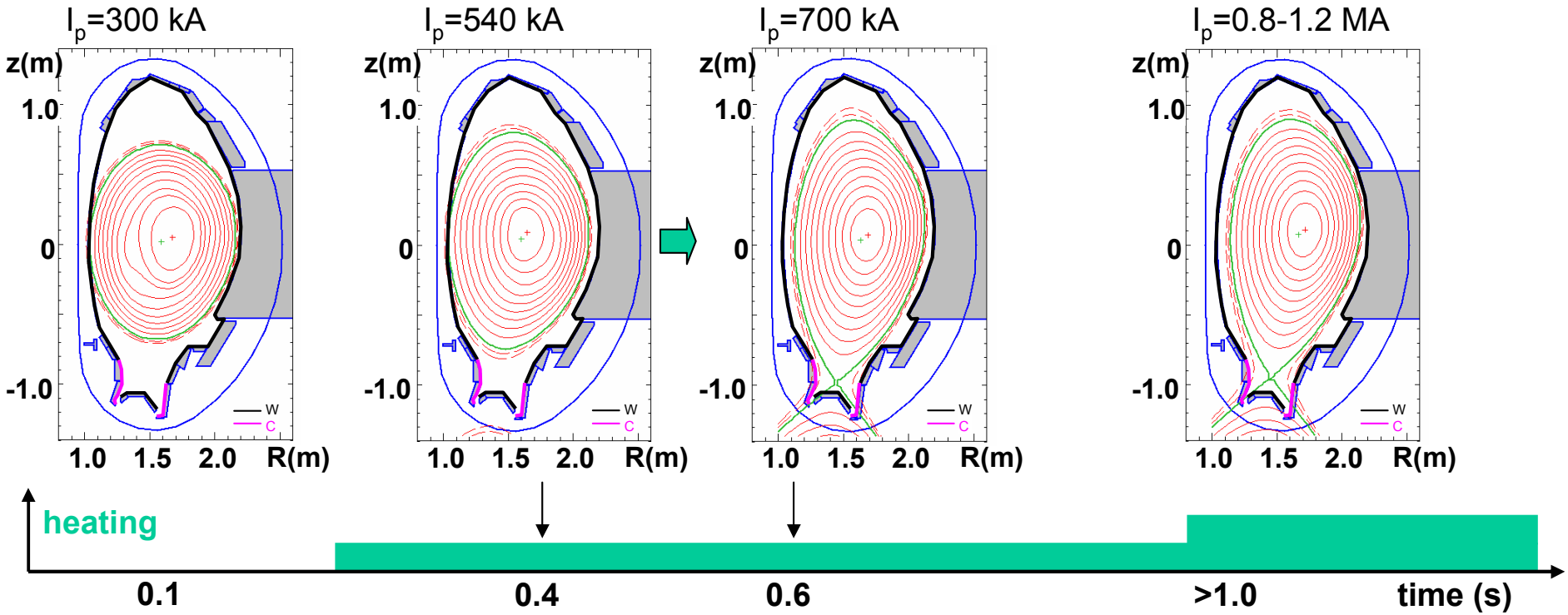
H-mode operation for a wide range of plasma conditions:

- I_p=0.6-1.4MA, B_T=1.6-3.0T.

All type I ELMy H-modes:

- q_{95} < 5.5, stationary > 0.2 s.
  (values shown are averaged)

Current rise phase → Low magnetic shear

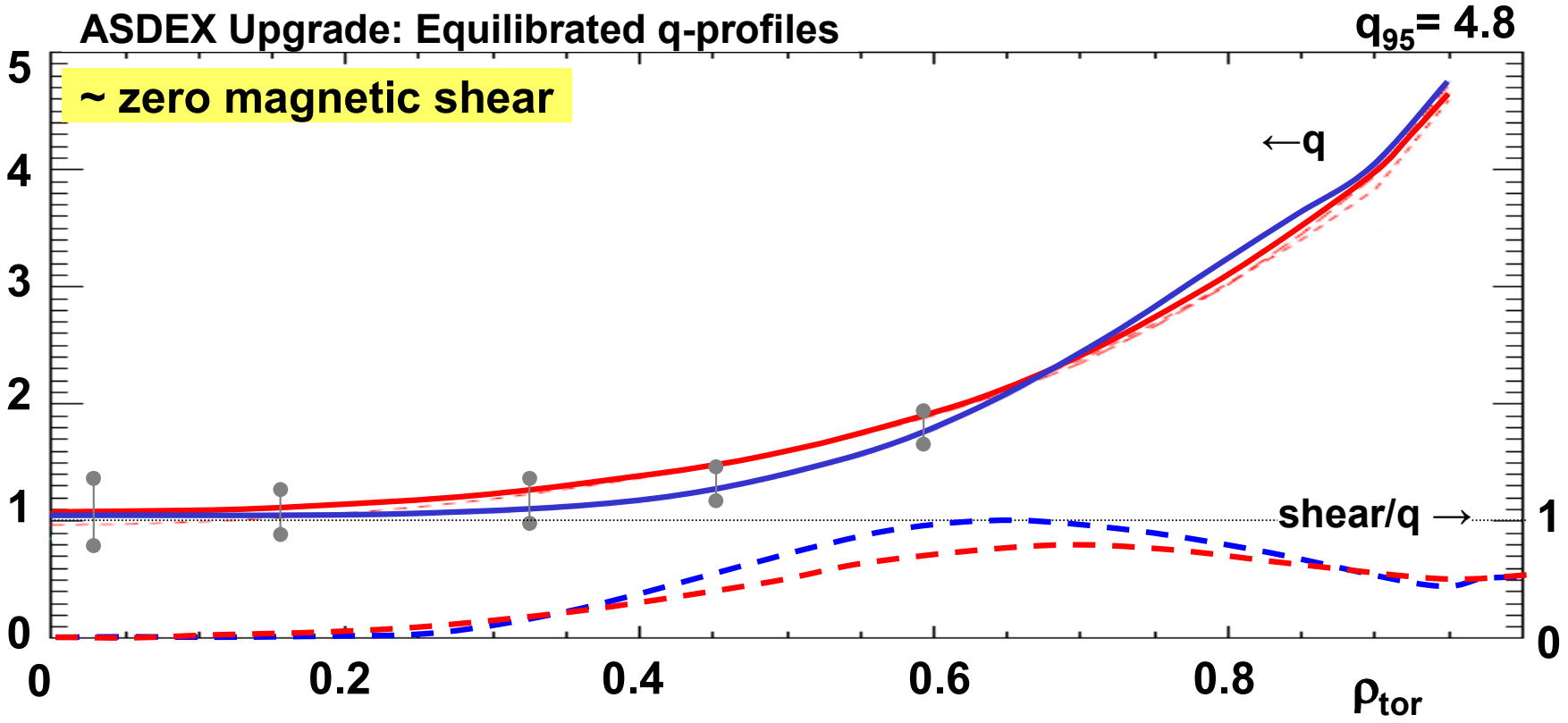


Current rise:

1. Early divertor configuration t~0.5s.
2. → low $\langle n_e \rangle$ ~ 3×10^{19} m^{-3}, control of impurities.
3. Additional heating: Slow down the current penetration.

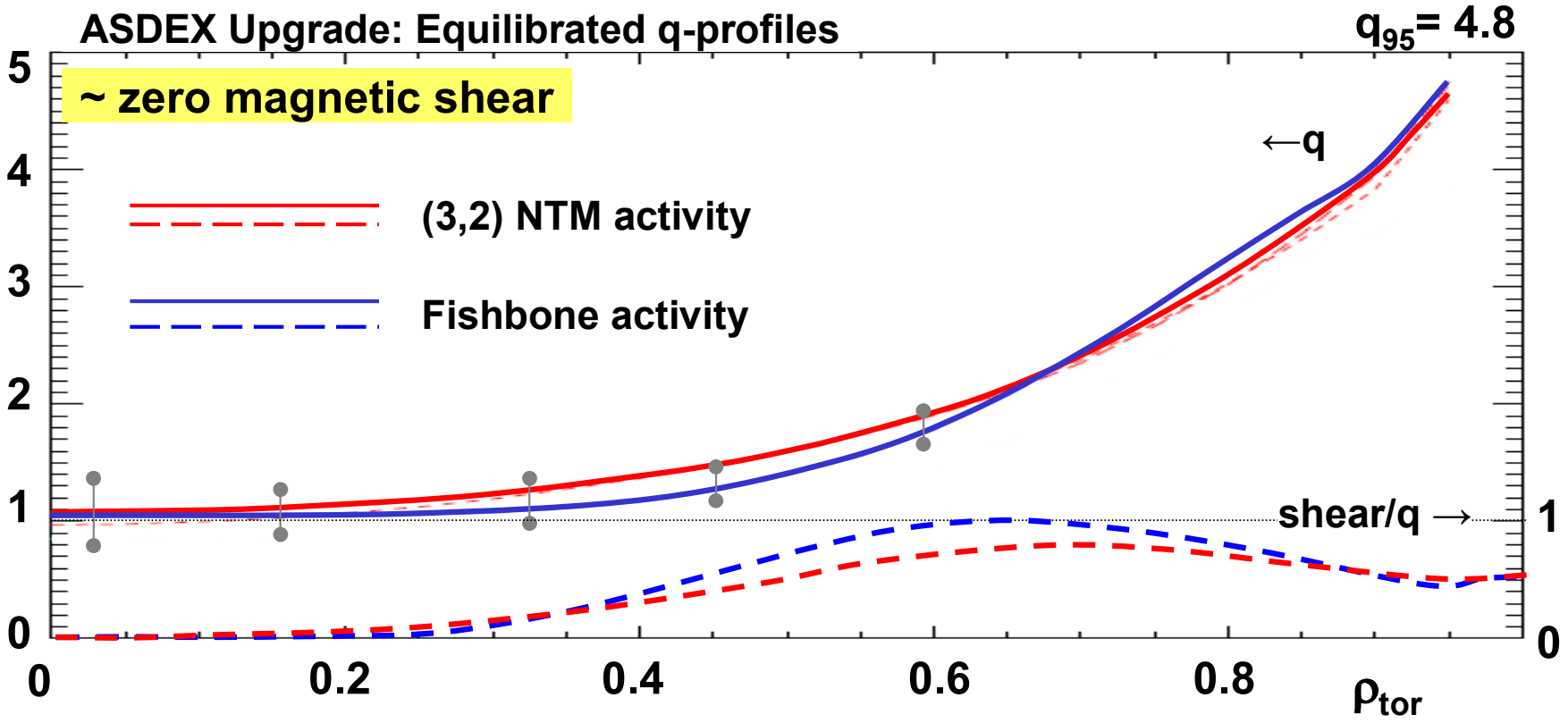
→ Low magnetic shear in the centre.

Low magnetic shear → Improved H-mode



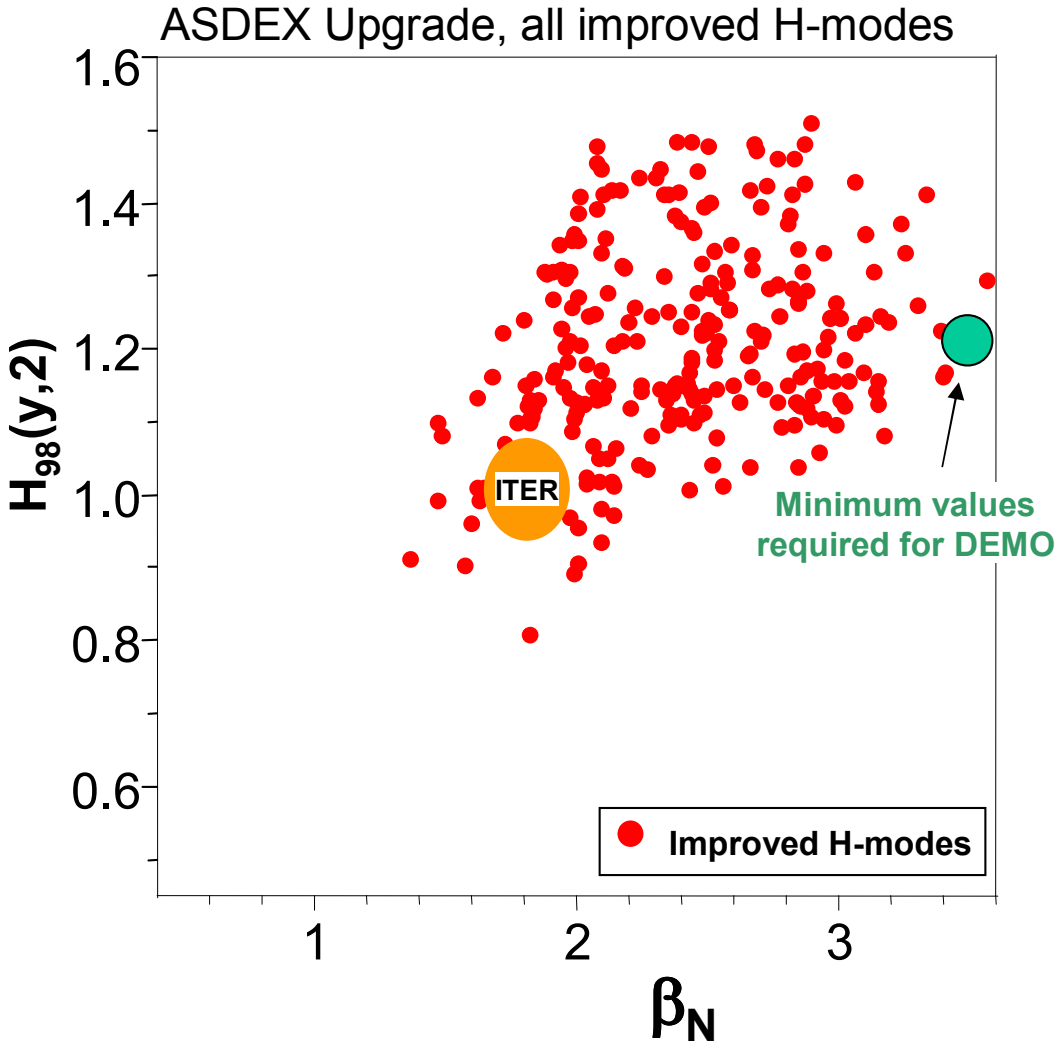
- MSE data available in 2006. ***McCarthy P. et al, EX/P3-7***
- Timing of preheating: 'control' of q-profile → $H_{98}(y,2)$. ***Stober J. et al, EX/P1-7***
- The q-profile remains flat in the core.

Low magnetic shear → Improved H-mode



- MSE data available in 2006.
- Timing of preheating: 'control' of q-profile → $H_{98}(y,2)$.
- The q-profile remains flat in the core. MHD modes main candidate.
  Typically (3,2) NTMs and higher (m,n) activity or fishbone activity.

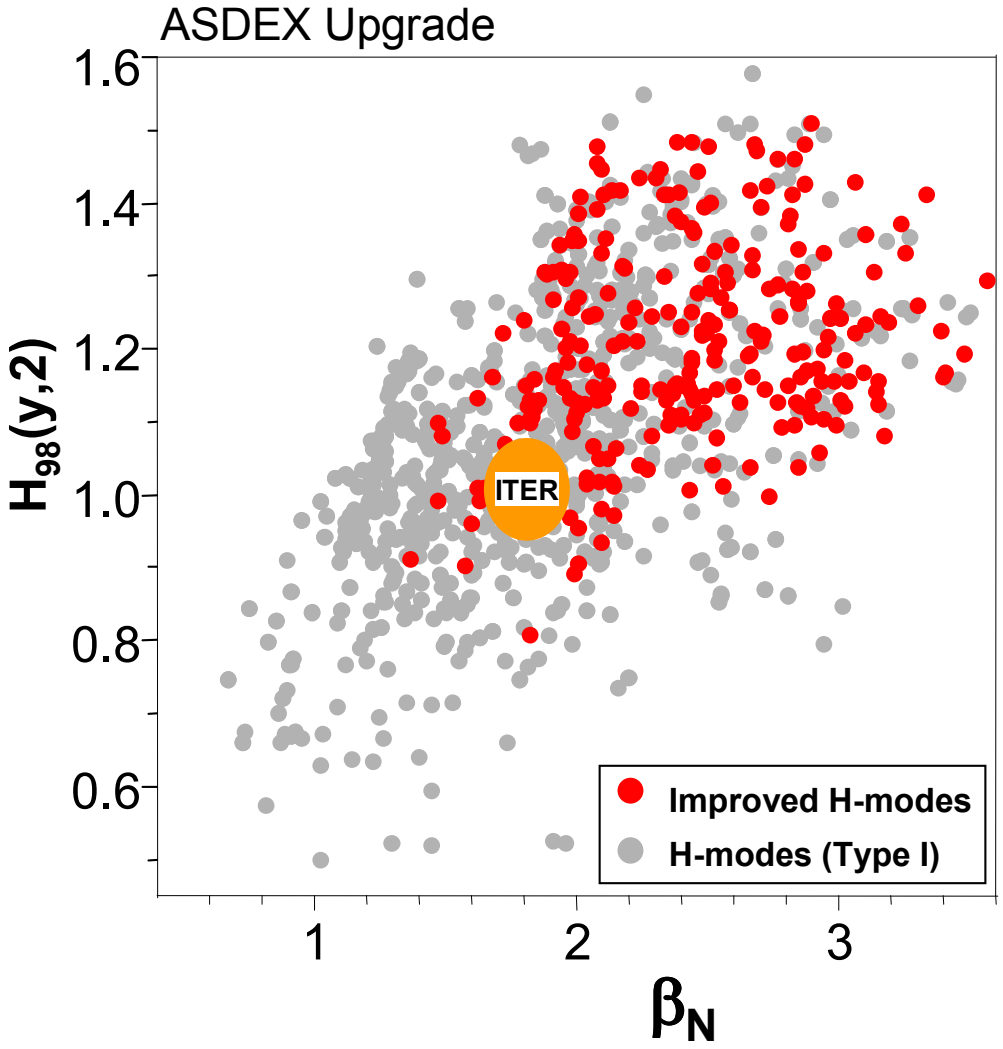
ASDEX Upgrade: Improved H-mode data



A second dataset includes **all** "improved H-mode" discharges:

- **Early heating** (some selected cases with late heating).
- Stationary for > 0.5 s.
- NOT just a selection of the best discharges.

ASDEX Upgrade: Improved H-mode data



Improved H-modes do not exclusively occupy the domain $H_{98}(y,2) > 1$ at $\beta_N = 2\text{-}3$.

Any H-mode, when it manages to achieve high beta is likely to develop low central shear in the centre, due to bootstrap current (overlap of 'grey' and 'red' data).

Physics criteria for improved H-modes would depend on the details of the current density profile (not routinely available).

ASDEX Upgrade: Improved H-mode data

Average values	Type I ELMy H-modes (944)	Improved H-modes (259)
q_{95}	4.1	4.0
$H_{98}(y,2)$	1.08	1.21
β_N	1.89	2.43
l_i	0.95	0.89

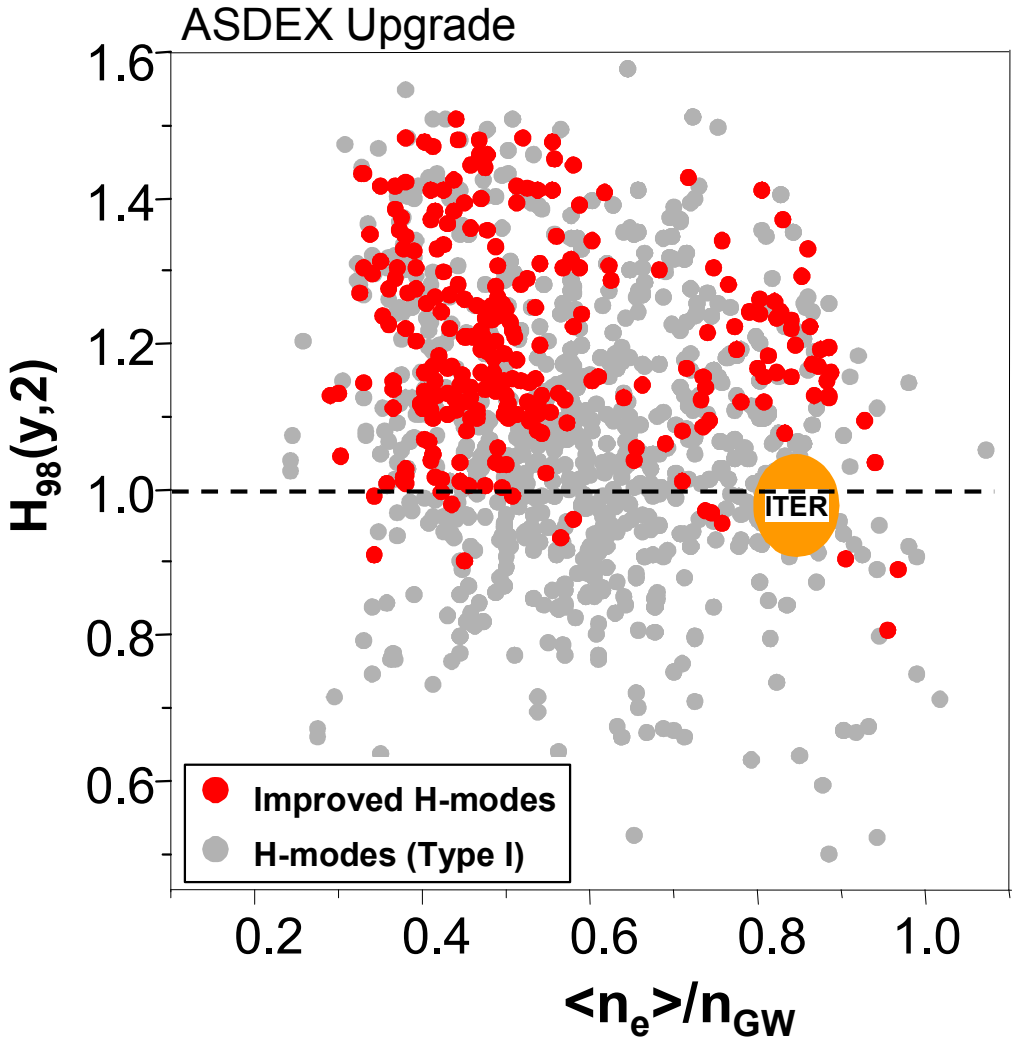
Various physics studies on the reason for the high stability/ confinement in improved H-modes.

Core: ***Stober J. et al, EX/P1-7***

Pedestal: ***Suttrop W. et al, EX/8-5***
Maggi C. et al, IT/P1-6
(various experiments)

Similar results have been obtained in other experiments (DIII-D, JET, JT-60U, NSTX..), for a range of conditions (See this conference !!).

Operational range: Density

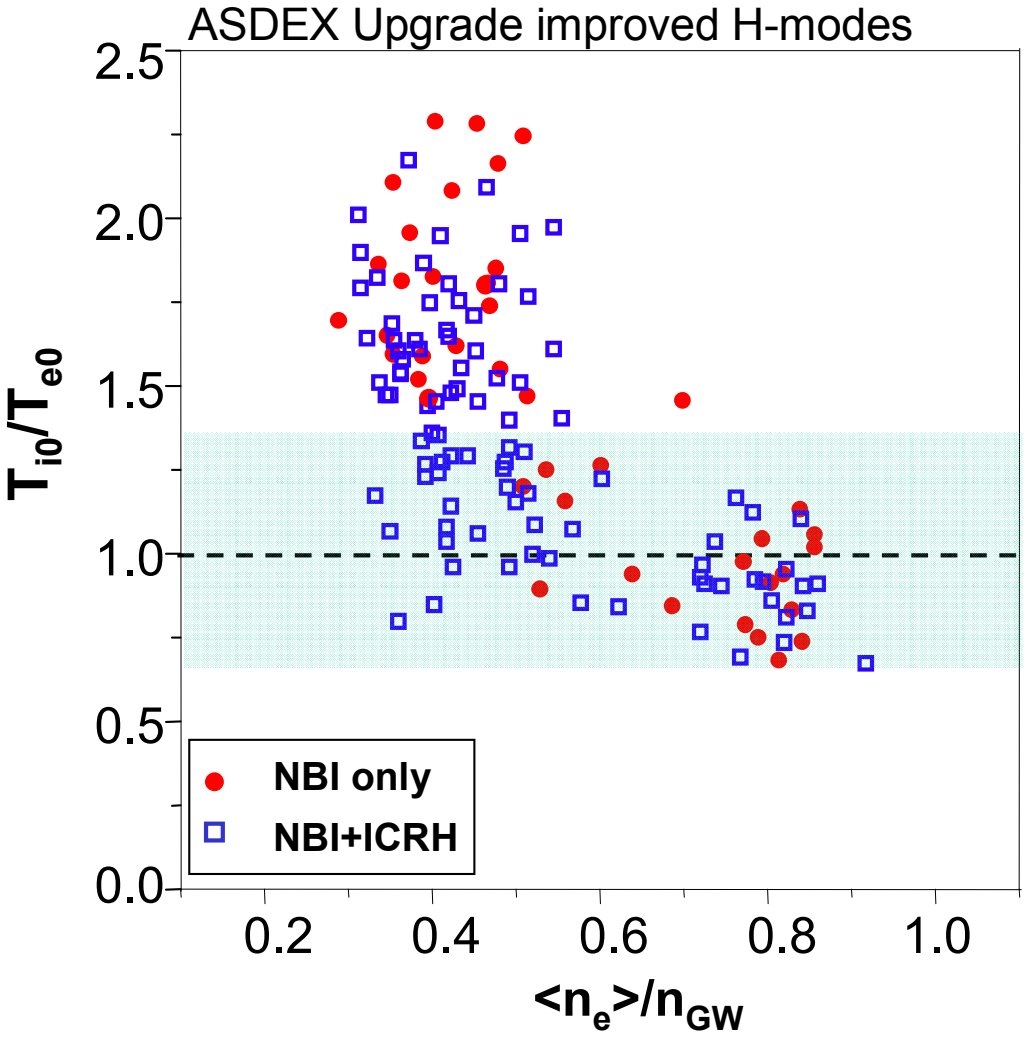


Improved H-modes:
Typically operate at low density,
$<n_e>/n_{GW}$ = 0.35-0.6.

After formation of q(r), the density can be increased <u>together</u> with an increase in heating power and δ.

$<n_e>/n_{GW}$ = 0.85, $H_{98}(y,2) \sim 1.2$ are obtained at high δ=0.4.
→ At 1MA: $<n_e>=1.1 \times 10^{20}$ m^{-3}.
→ Tolerable ELMs.

Operational range: T_{i0}/T_{e0}



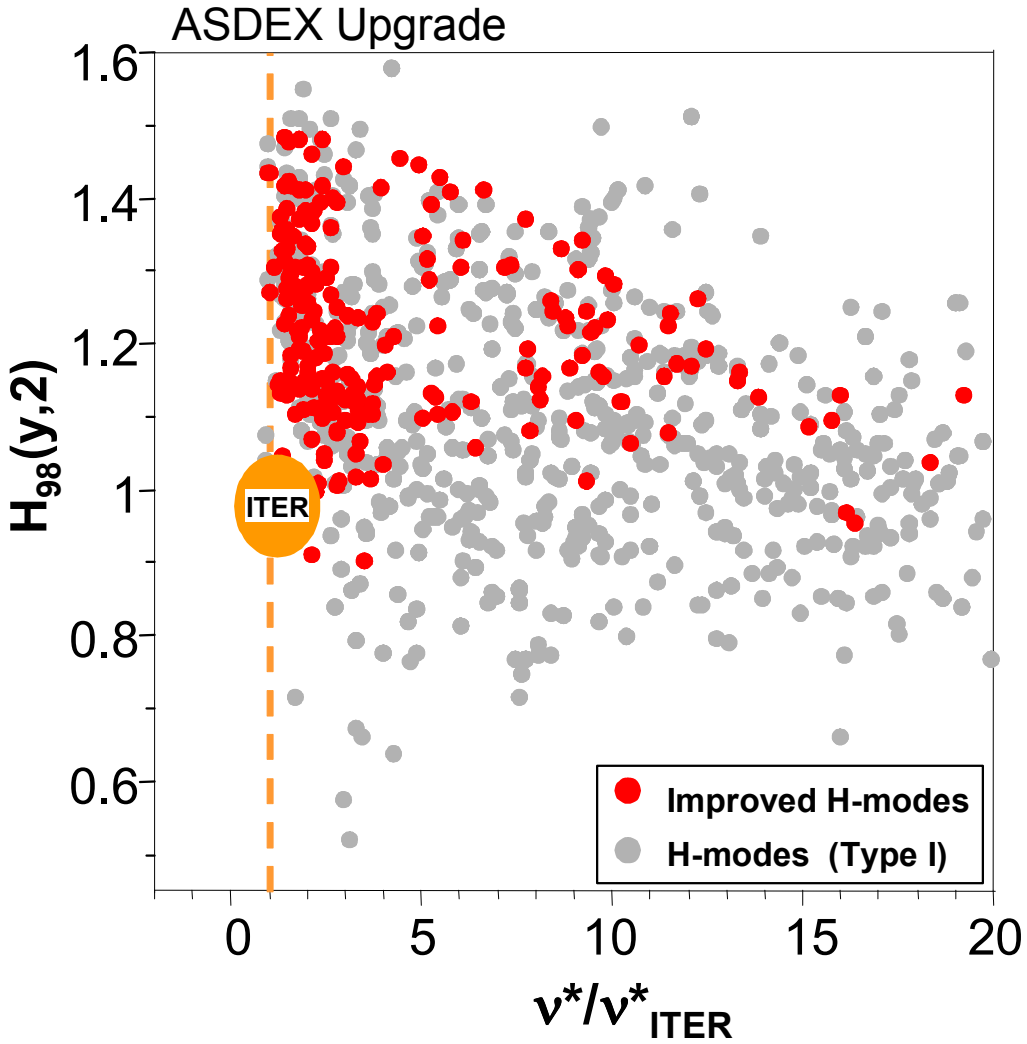
1. Operation at high $<n_e>$.
2. ICRH and NBI at low $<n_e>$.

→ **$0.7 < T_{i0}/T_{e0} < 2.5$**

T_{i0}/T_{e0} ~ 1 for a substantial subset of the data, while maintaining high confinement.

Moreover, some of these discharges have low plasma rotation (low momentum input).

Operational range: ν^*



Strongest correlation of maximum $H_{98}(y,2)$ with plasma collisionality (ν^*/ν^*_{ITER}).

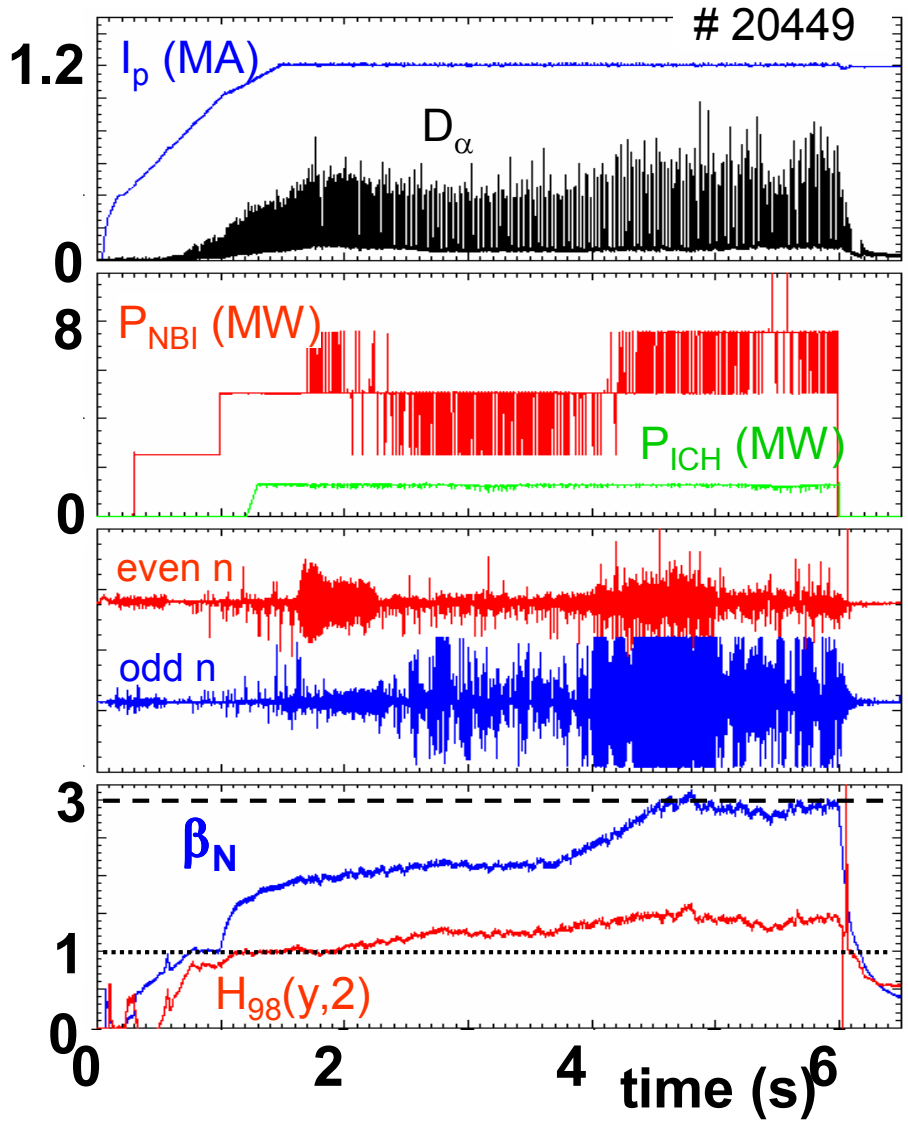
Also density peaking ($n_{e0}/\langle n_e \rangle$) can be higher at lower ν^*/ν^*_{ITER}.

Weisen H. et al, EX/8-4

→ β and ν^* dependence of the IPB98(y,2) scaling expression are under investigation.

McDonald D. et al, EX/P3-5

Operational range: low q_{95}=3.17



1.2MA/2.0T → q_{95} = 3.17,

- NBI used with beta feedback, 50% of NBI is off-axis! Central ICRF heating.
- $\langle n_e \rangle = 6.4 \times 10^{19} m^{-3}$, T_{i0}/T_{e0}=1.4 $\langle n_e \rangle / n_{GW}$=0.42, ν^*/ν^*_{ITER}=2.
- $H_{98}(y,2)$ rises to 1.4 at β_N=2.9.
- $C_{W,core}$ = 2.5×10^{-5} ($< 10^{-4}$).

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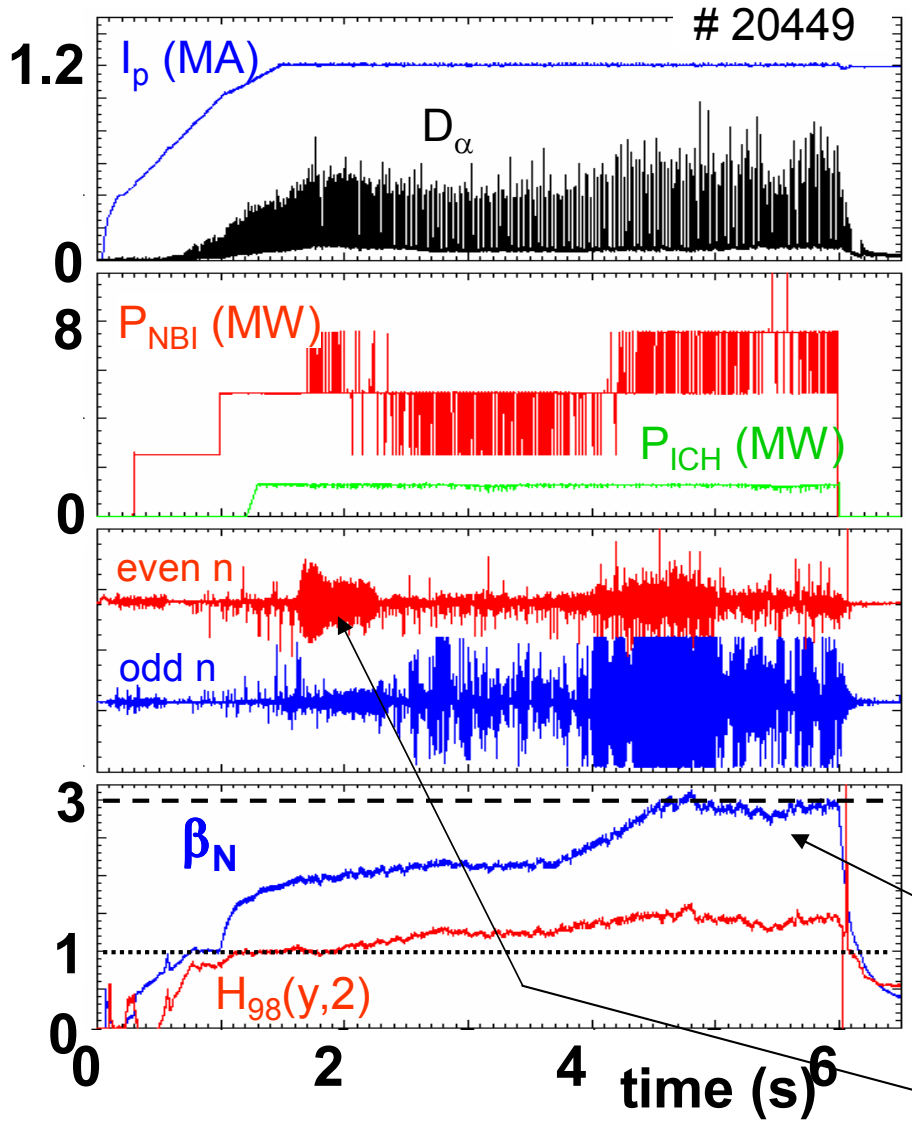

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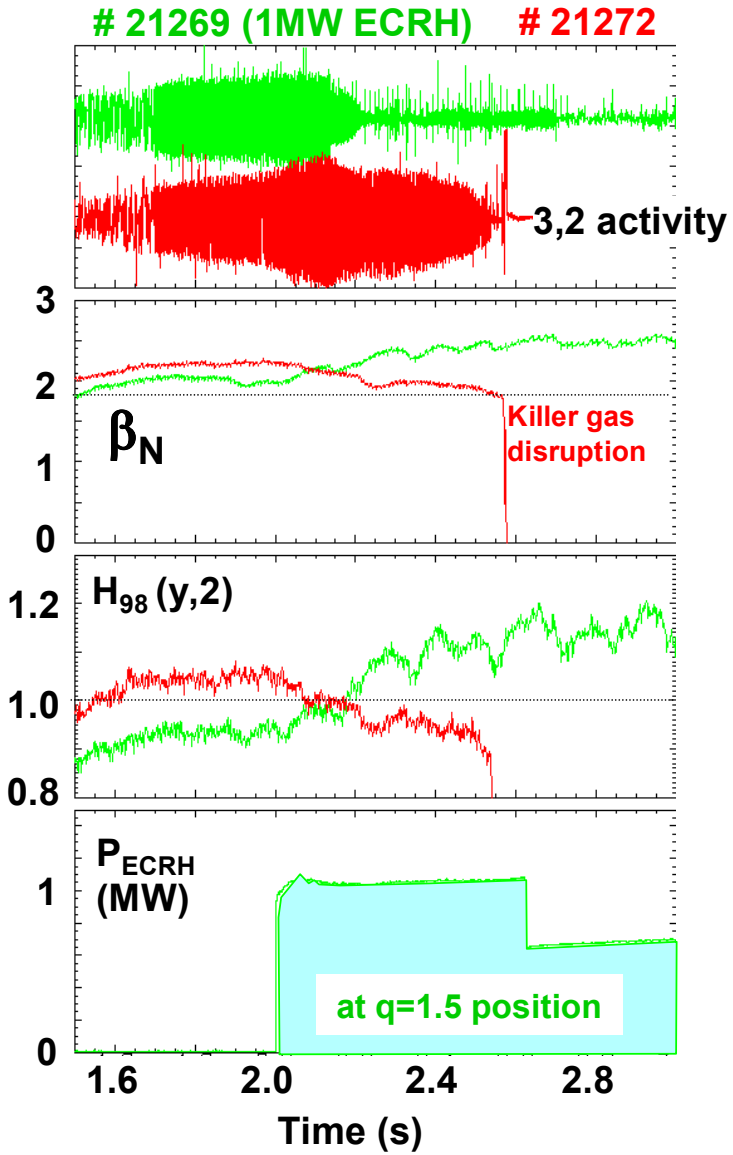
Core MHD:

- (1,1) fishbones.
- (4,3) NTMs.
- NO sawteeth.

Early (3,2) NTM when β_N ~2.

Operational range: ECCD, stabilise (3,2) NTM



1. ECCD: Stabilise this (3,2) NTM at q_{95}~3.1

After ECCD, discharge continues as improved H-mode (shown before).

Zohm H. et al, EX/4-1Rb

2. Otherwise (2,1) NTM may develop, and disruption recognition algorithms will act: (mode-lock, radiation peaking, regime identification, neural net):

- React by issuing a soft stop or triggering killer gas injection.

Pautasso G. et al, EX/P8-7

3. Stabilisation of (3,2) NTM is **not required** for improved H-modes with $q_{95} > 4$.

Stober J. et al, EX/P1-7

Scaling to ITER using experimental data

Motivation:

- Integrated simulation codes rely on use of transport models and models for actuators, require benchmarking on current experiments.
- **Scaling the measured kinetic profiles to ITER:** 100% fit to experimental data, gradient length preserved, pedestal.
  - Use experimental profile shapes.
  - Same β_N, H-factor's.
  - Use ITER geometry.
  - Impurities: Be 2 %, Ar 0.12 %, He 4.3 % → $(n_D+n_T)/n_e \sim 0.8$.

Luce T. et al 2004 Phys. Plasmas 11 2627

Assemble set of discharges with good profile measurements.
ITER predictions: P_{fus}, P_{aux}, Q (+ other parameters using ASTRA).

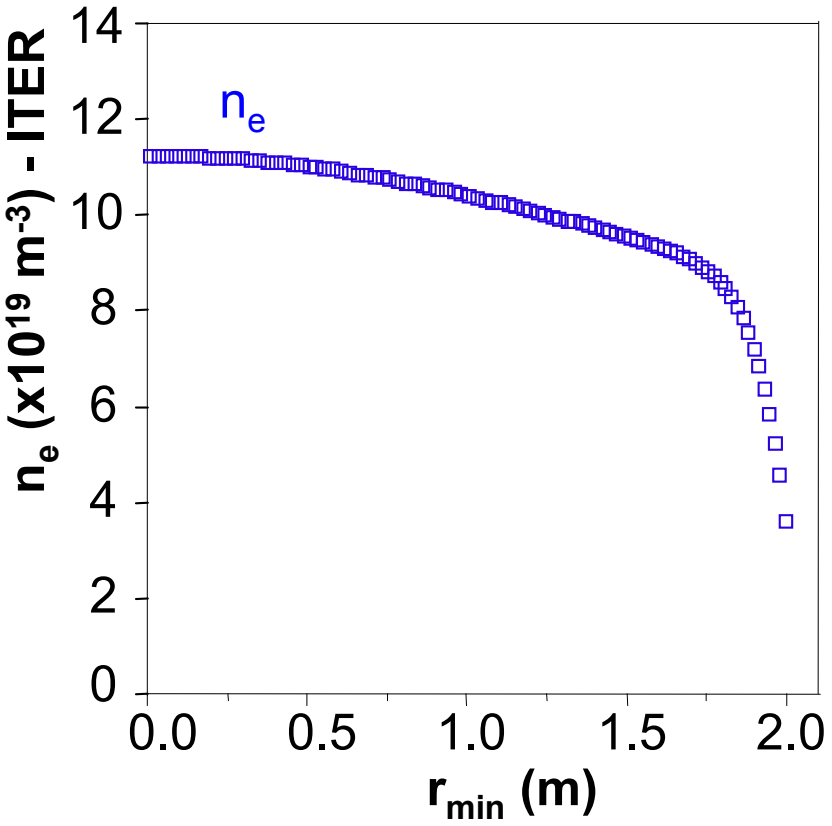
Tardini G. et al 33rd EPS Conference, Rome 19-23 June 2006, P1.112

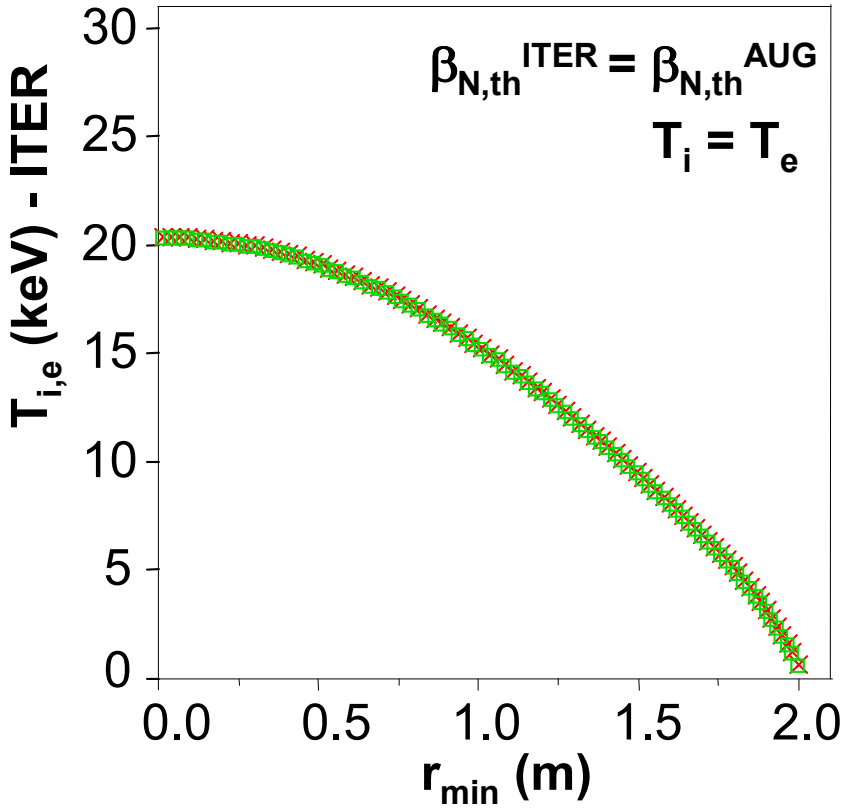
Scaling to ITER using experimental data

Density: Use shape of n_e profile from ASDEX Upgrade, **set $\langle n_e \rangle = 0.85 n_{GW}$.**

Temperatures: Use shape of T_i profile or use shape of T_e profile from ASDEX Upgrade (select highest), **set $T_i = T_e$ and $\beta_N^{ITER} = \beta_N^{AUG}$.**

Scaling to ITER: q_{95}=3.0, β_N=2.1, high $\langle n_e \rangle$





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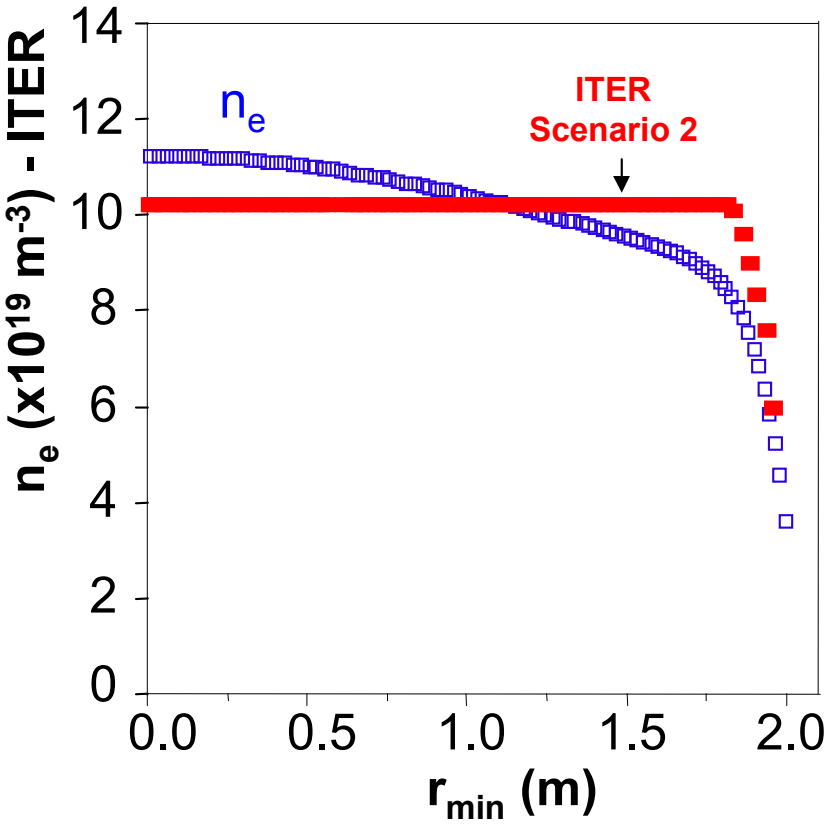
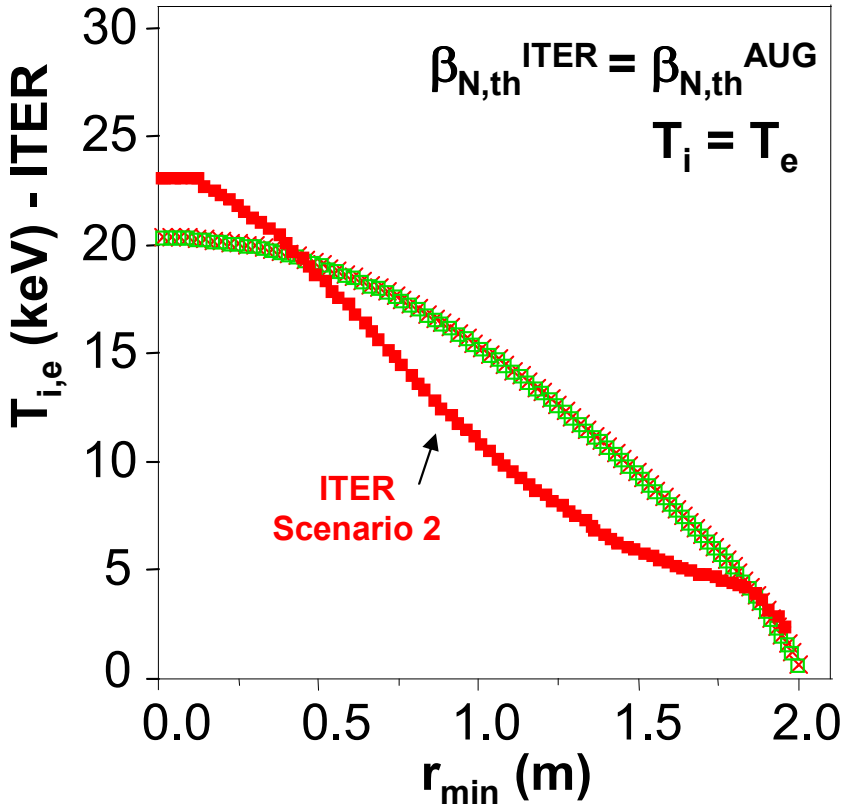
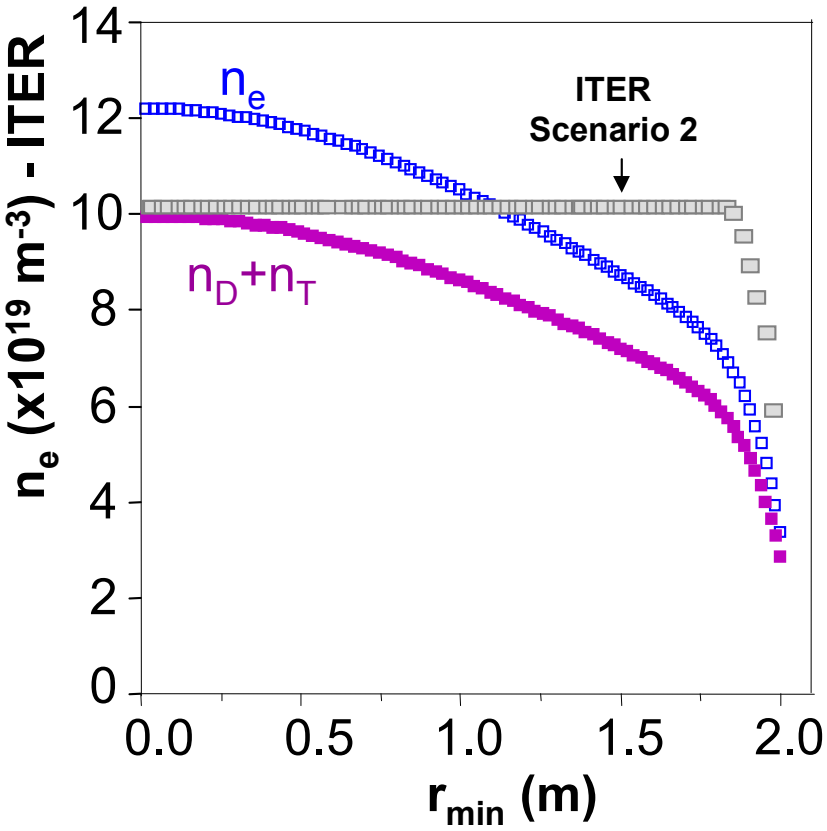


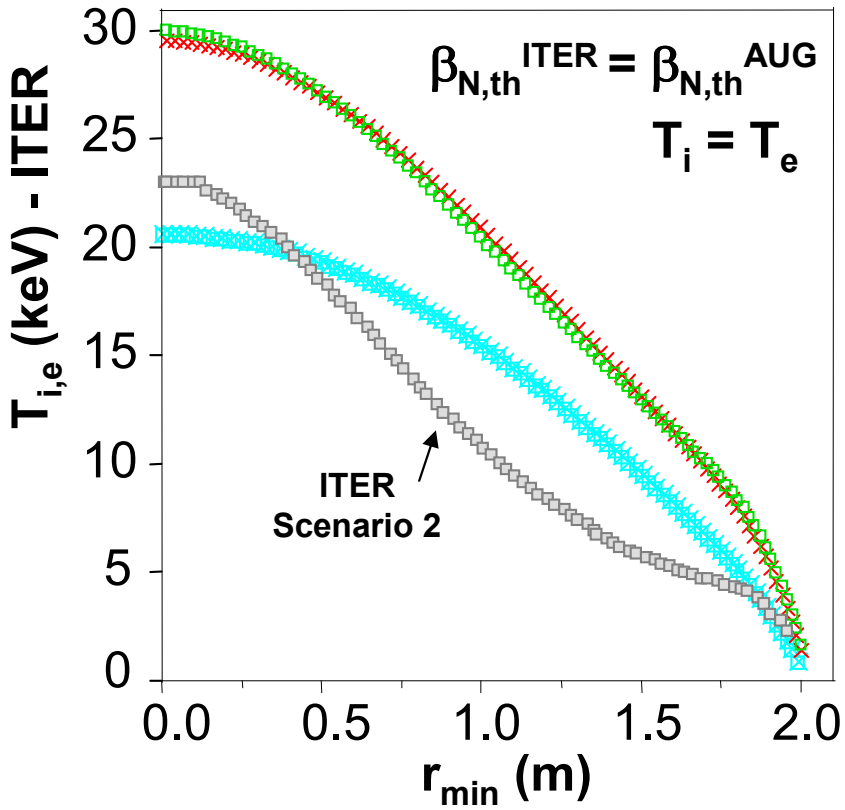


Comparison with integrated ITER scenario modelling (Scenario 2):

- **Density:** Assumed flat.
- **Temperatures:** Set pedestal, models for core transport & heating systems.

Scaling to ITER: q_{95}=3.17, β_N=2.9



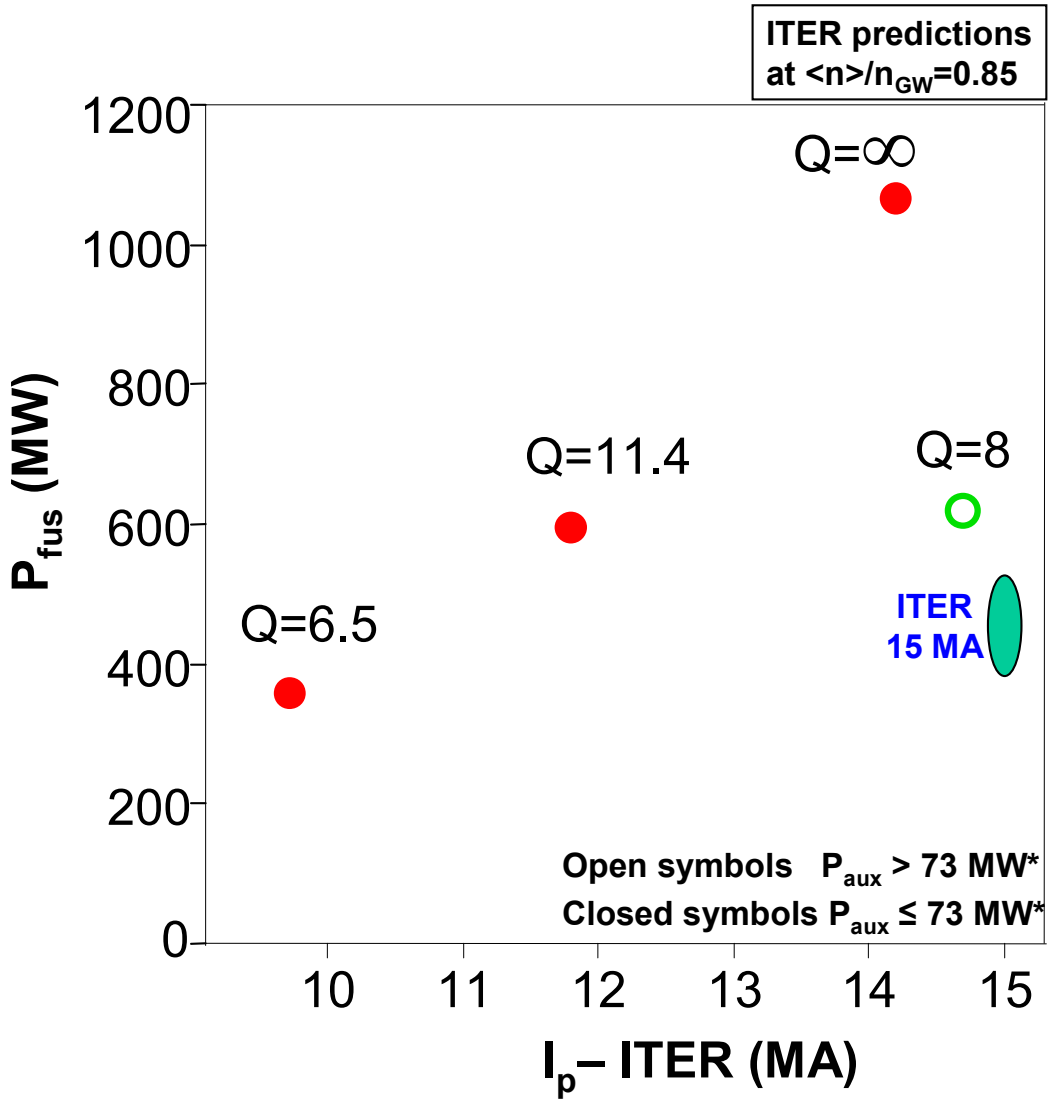


At higher β_N (Improved H-mode):

- Temperature profiles rise over whole plasma region.
- Consistent with observations of increased edge pedestal.

Suttrop W. et al, EX/8-5
Maggi C. et al, IT/P1-6

Prediction of fusion performance in ITER



4 typical cases:

q_{95}	β_N	$H_{98}(y,2)$
3.05	2.10	0.95
3.17	2.87	1.40
3.8	2.63	1.32
4.6	2.41	1.44

*P_{aux} based on using IPB98(y,2) scaling.

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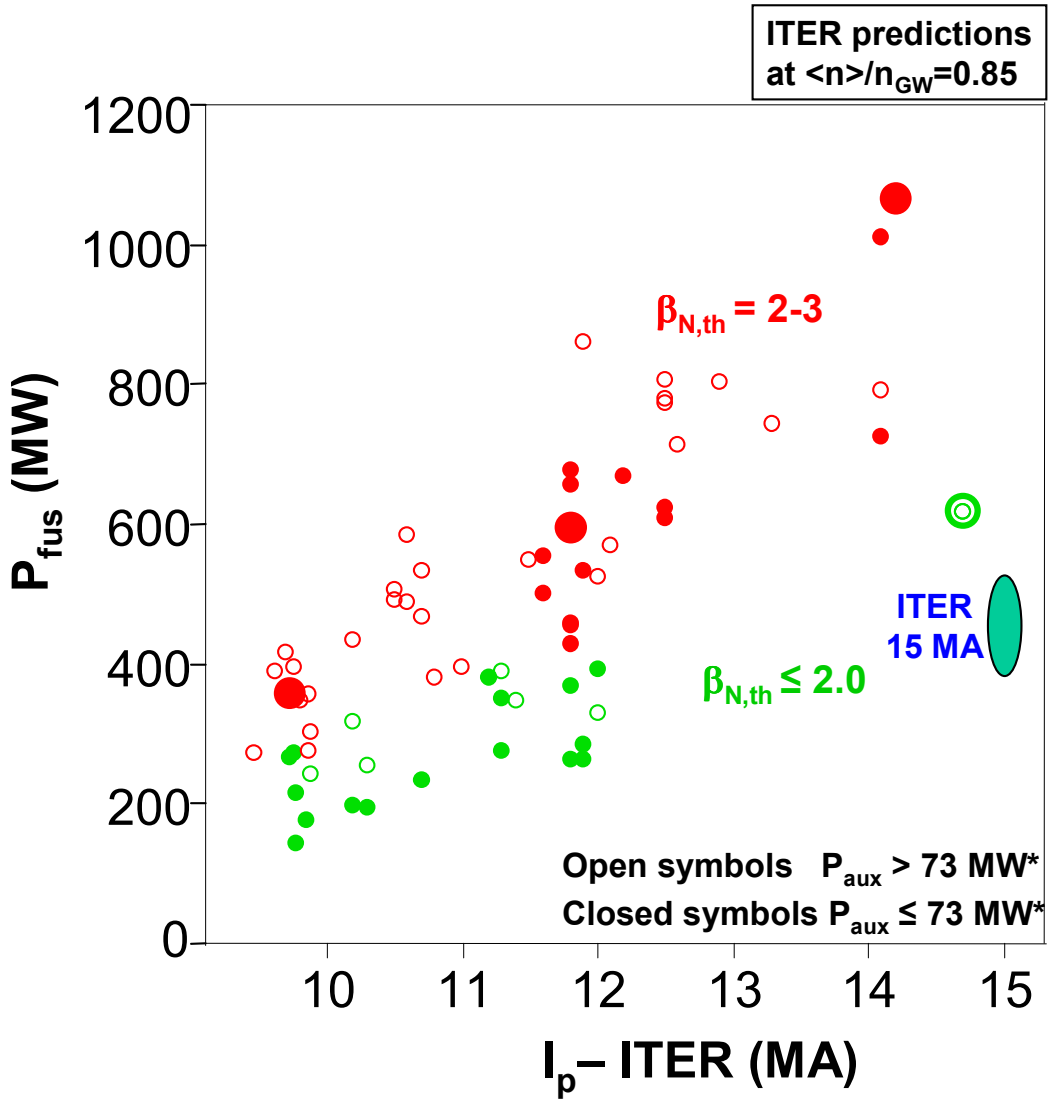
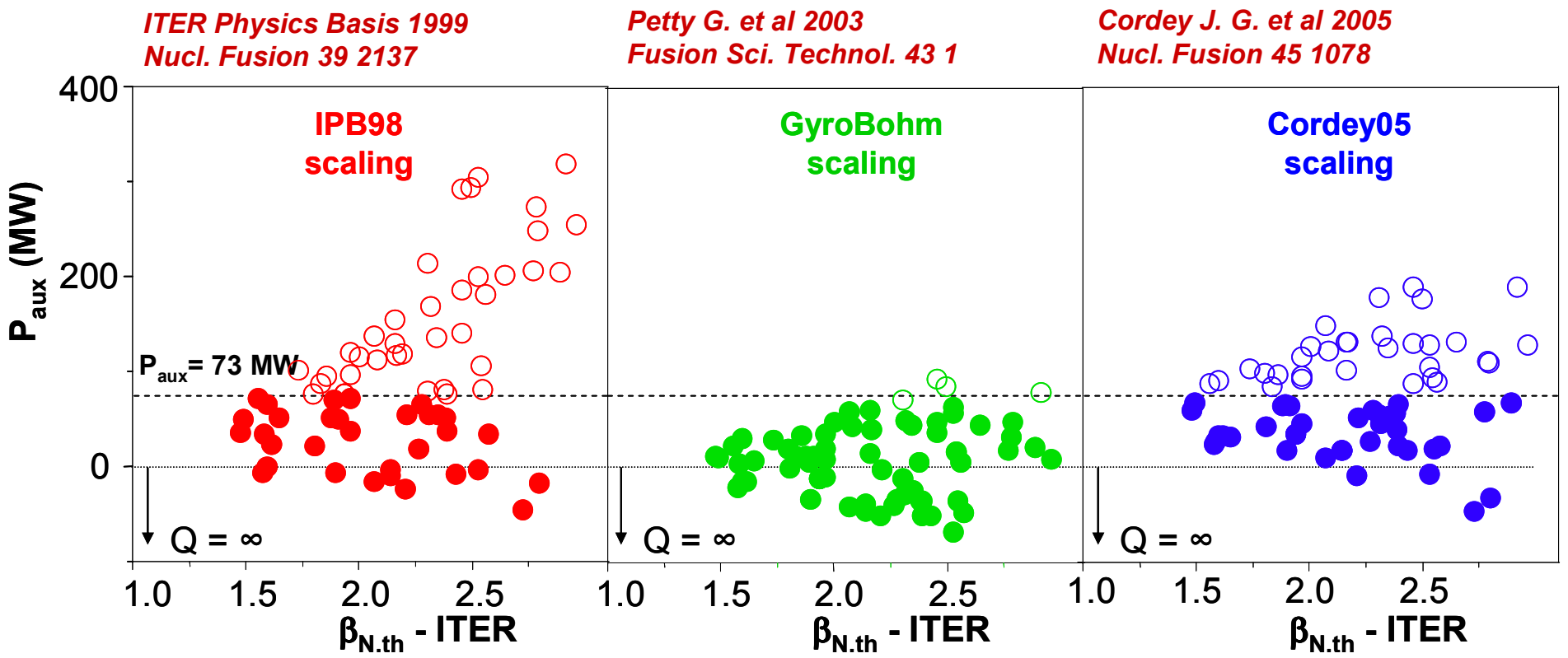


*P_{aux} based on using IPB98(y,2) scaling.

Operation at $\beta_{N,th}$ =2-3:

- Significant fusion power for I_p=9.5MA to I_p=12MA. With bootstrap current fraction f_{BS}~0.4 , and Q=6-15. Long pulse lengths (> 400s).
- At low q_{95}~3 (I_p=14-15 MA) would in principle be able to reach P_{fus}~1GW, Q=∞.

Prediction of fusion performance in ITER



Q and input power (P_{aux}) required (ASDEX Upgrade profile data):

- Calculated for three different energy confinement scaling expressions.
- Using IPB98(y,2): In some high β cases : P_{aux} > 73MW.
  I_p <11MA, despite $H_{98}(y,2)$~1.4.

Conclusions

ASDEX Upgrade:

H-modes with low magnetic shear in the centre: $H_{98}(y,2) > 1$ and β_N=2-3.5.

- Operation at high density and $T_{i0}/T_{e0} \sim 1$ is demonstrated.
- Highest $H_{98}(y,2)$ values are achieved at ITER relevant ν^*.
- At q_{95}=3.1: $H_{98}(y,2)$=1.4, β_N=2.9, fishbone activity keeps q(r) stationary.
- ECCD can be used to stabilise (3,2) NTM activity (q_{95}~3).

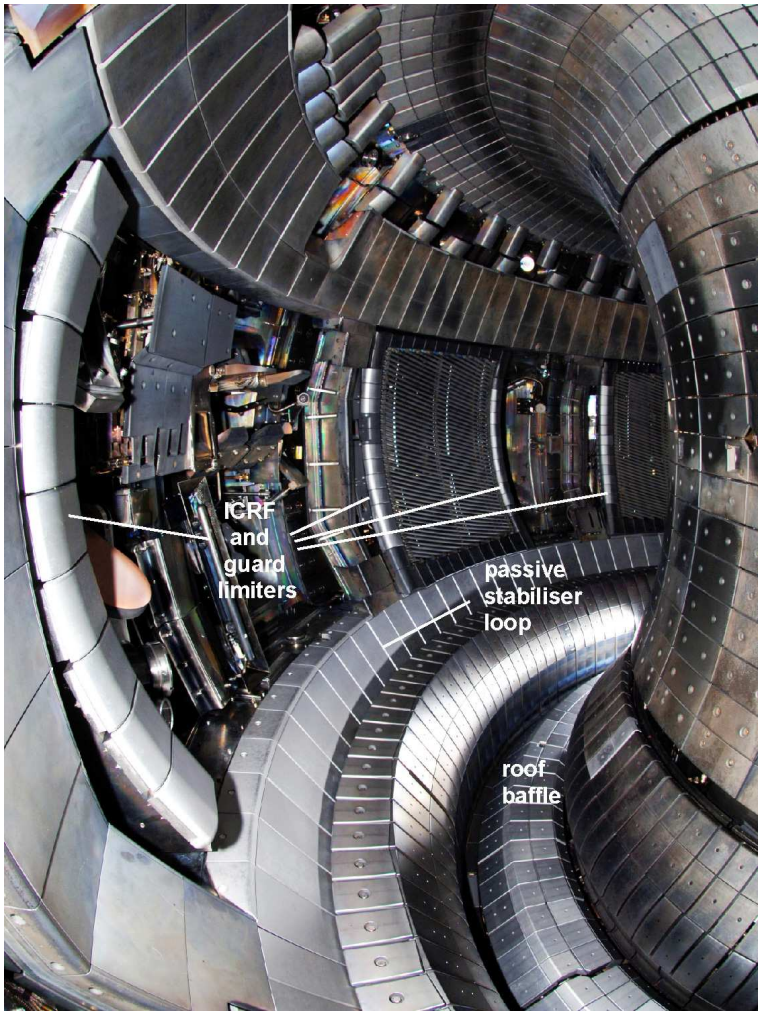
ITER predictions, scaling kinetic profile shapes : $\langle n_e \rangle = 0.85 n_{GW}$, keep $\beta_{N,th}$.

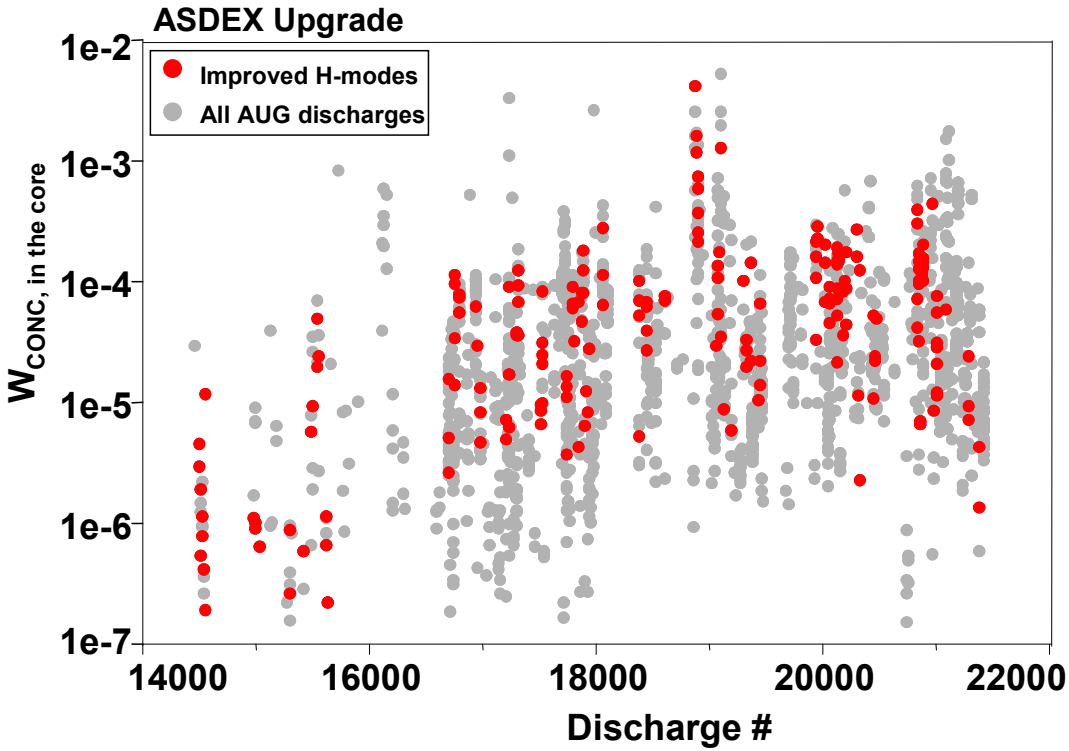
At q_{95}=3.1: P_{fus}=1070 MW, Q=∞.

At I_p=9.5-12MA: P_{fus} 300-600 MW, Q=6-15 (some cases P_{aux}>73 MW).

Back-up slides

Operation: Tungsten coverage → 85%





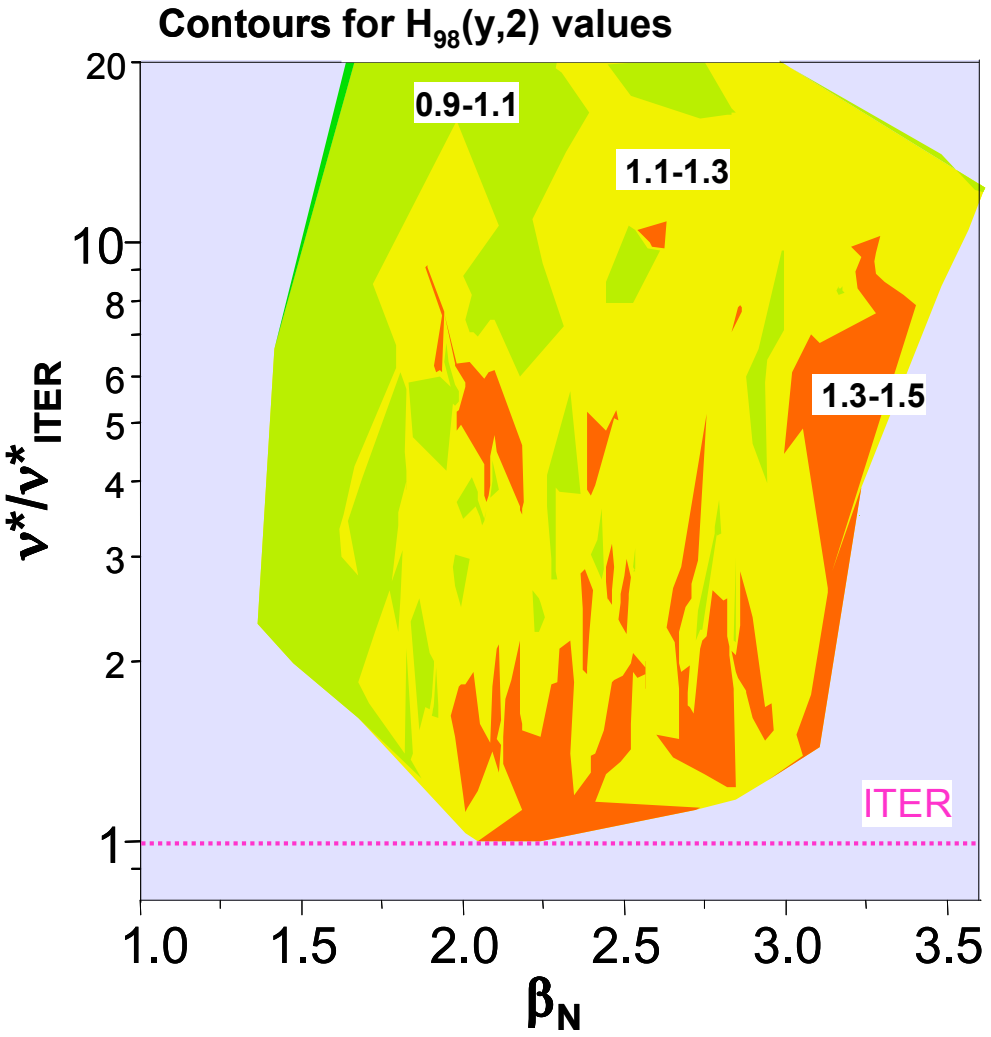
All H-modes require central ICRH or ECRH to avoid impurity accumulation.

Operation at $\langle n_e \rangle \sim 4\text{-}6 \times 10^{19}$ m^{-3} requires a boronisation to minimise tungsten influxes.

Gruber O. et al, OV/2-3

Dux R. et al, EX/3-3Ra

Operational range: Density, ν*



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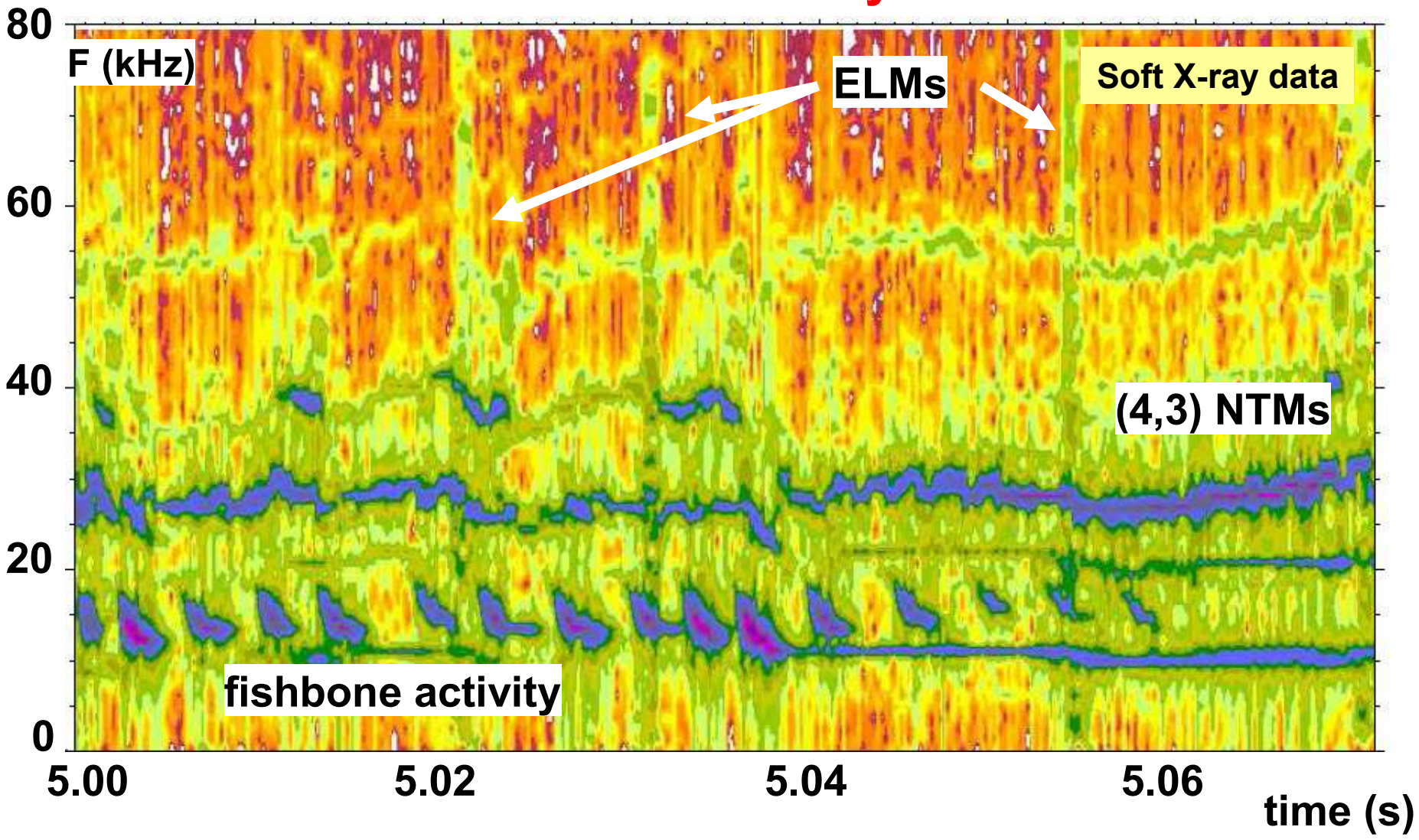
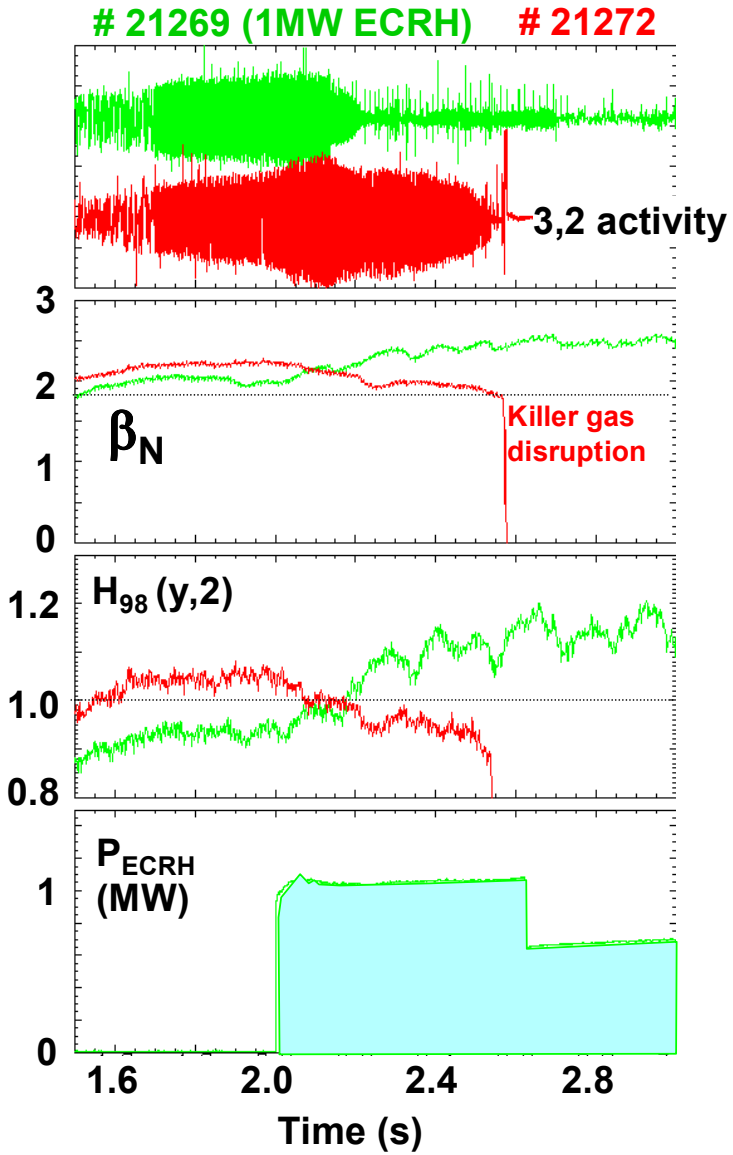
McDonald D. et al, EX/P3-5

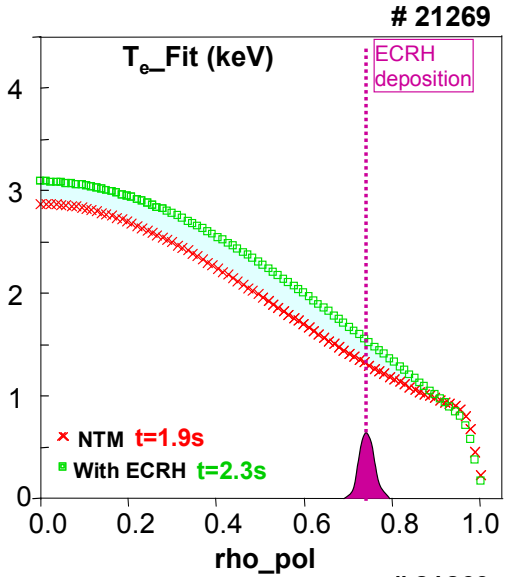
Operational range: low q_{95}=3.17

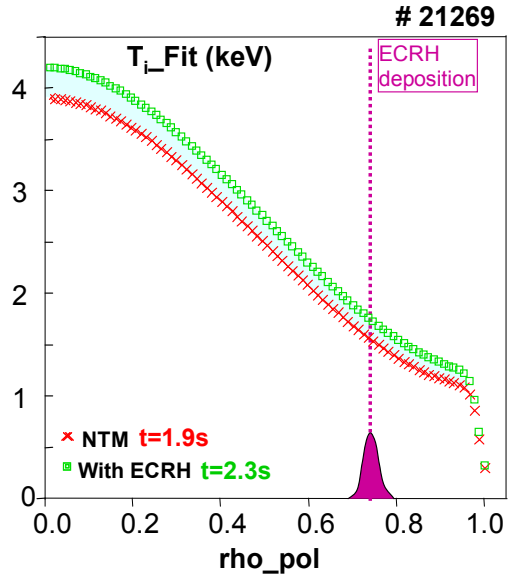
Core MHD activity

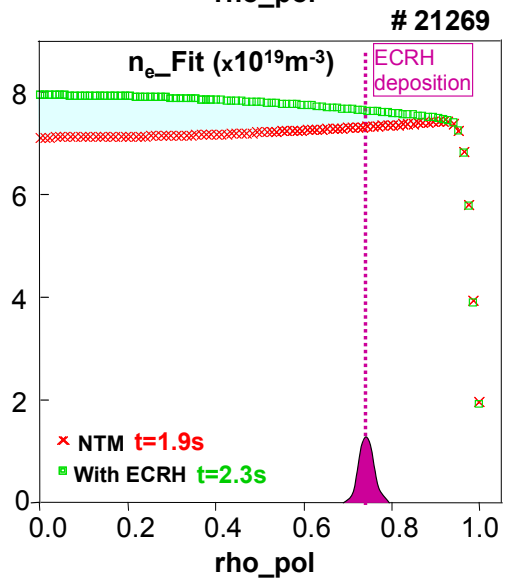


Use of ECCD to stabilise (3,2) NTM





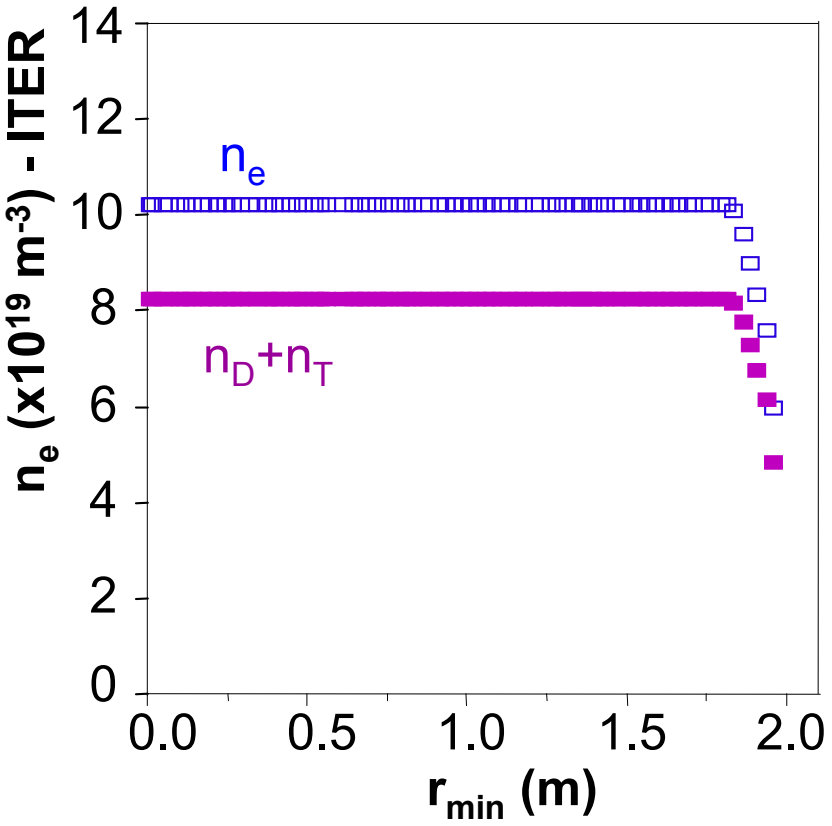


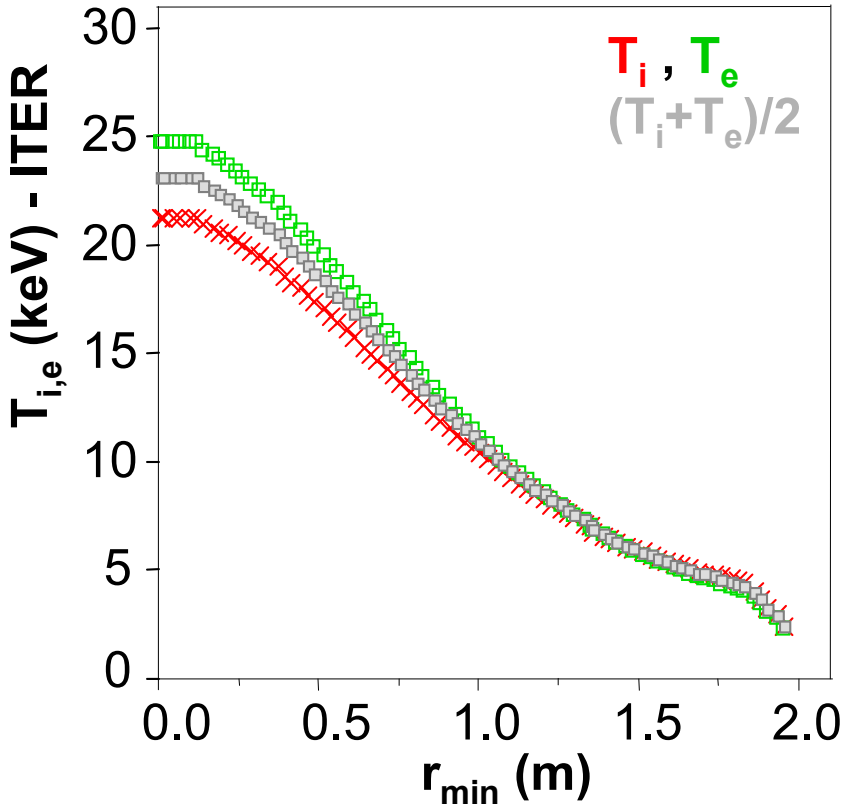


Zohm H. et al, EX/4-1Rb

ITER Scenario 2

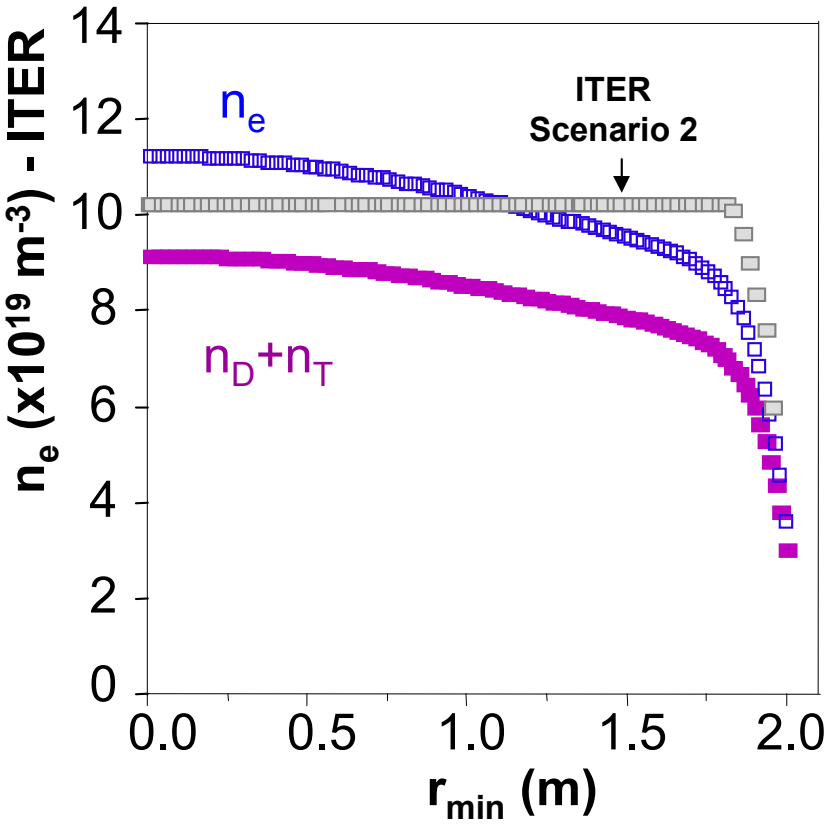
ITER Physics Basis 1999 Nucl. Fusion 39 2137

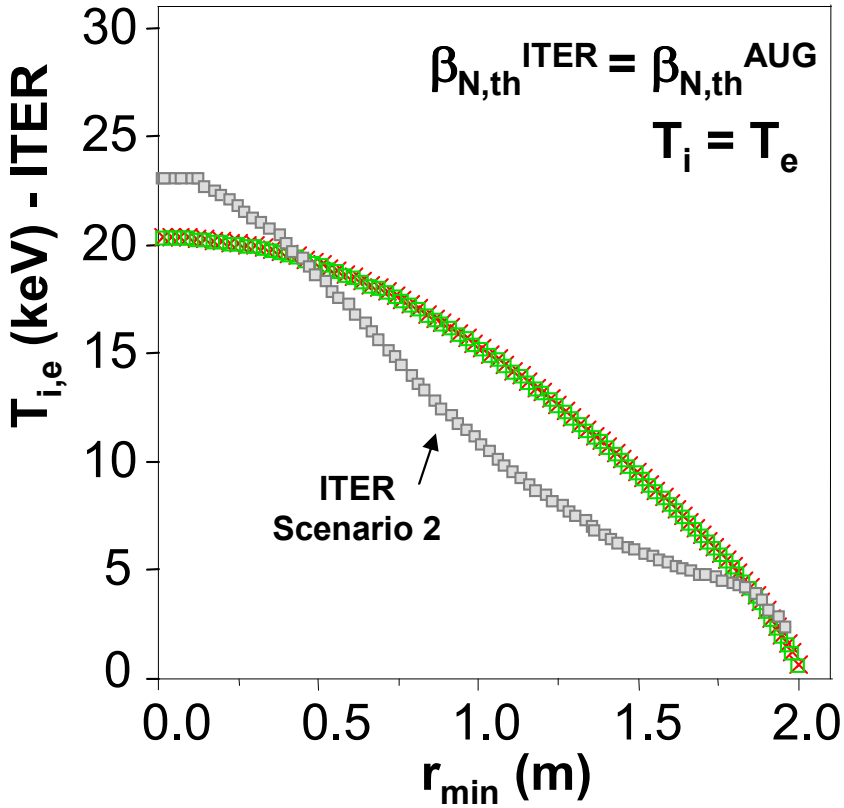




$<n_e>/n_{GW}$ =0.85	q_{95}	I_p (MA)	β_N	P_{fus} (MW)	$H_{98}(y,2)$	Q	P_{aux} (MW)	$<n_e>$ (10^{19}m^{-3})	n_{e0} (10^{19}m^{-3})	T_{e0}/T_{i0} (keV)
ITER Sc. 2	3.0	15.0	1.8	400	1.0	10	40	10.1	10.2	24.8/ 21.2

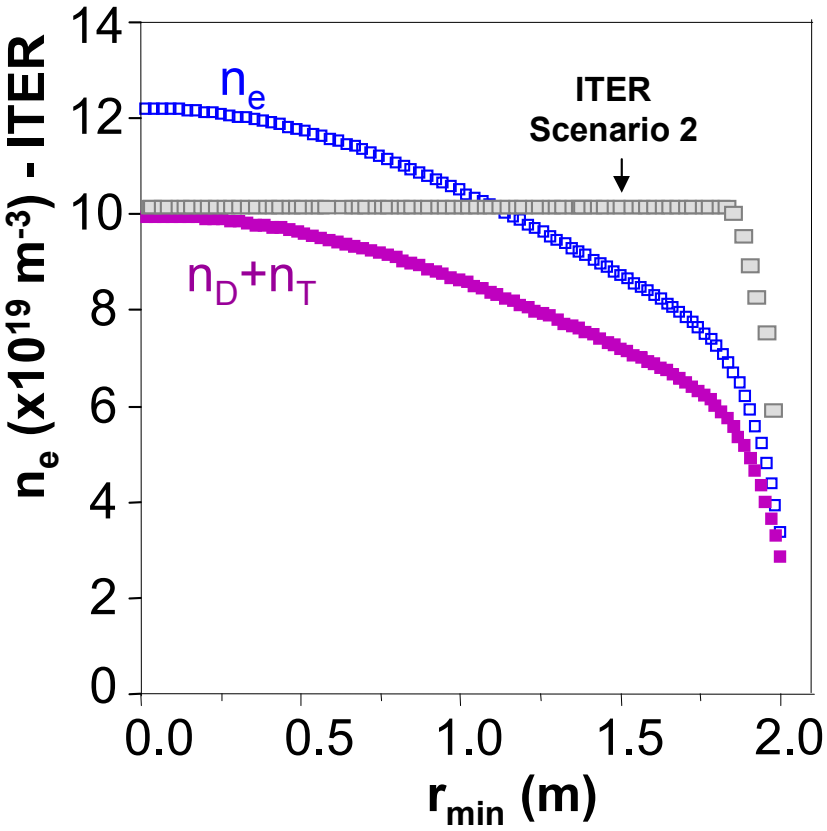
Scaling to ITER: q_{95}=3.0, β_N=2.1, high $\langle n_e \rangle$

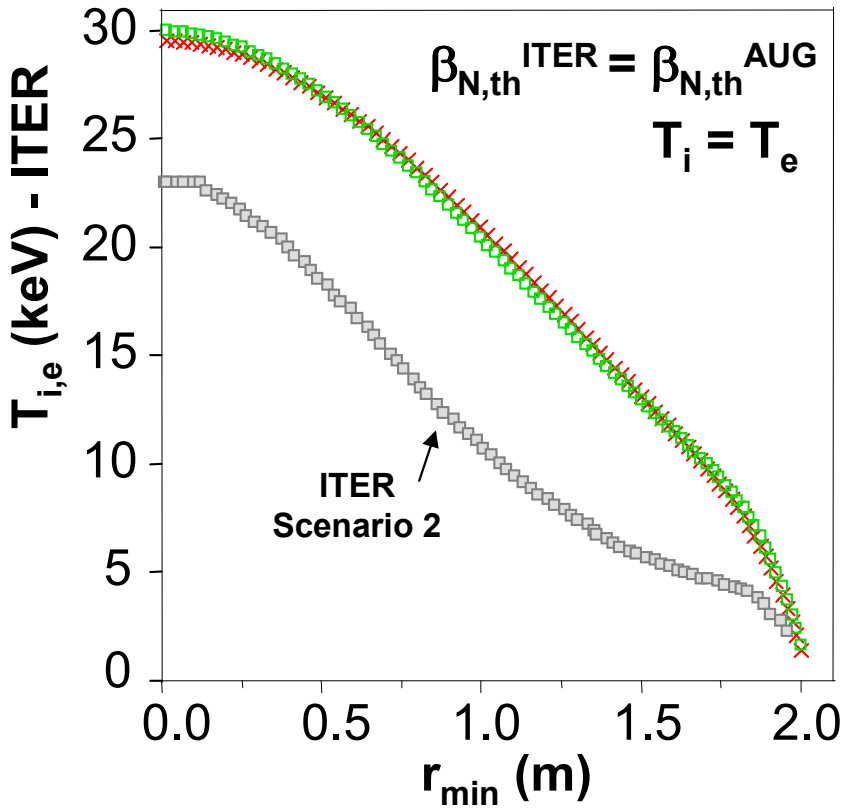




$\langle n_e \rangle / n_{GW}$ =0.85	q_{95}	I_p (MA)	β_N	P_{fus} (MW)	$H_{98}(y,2)$	Q	P_{aux} (MW)	$\langle n_e \rangle$ (10^{19}m^{-3})	n_{e0} (10^{19}m^{-3})	T_{e0}/T_{i0} (keV)
AUG #17847	3.05	14.7	2.10	619	0.95	8.0	(78)	9.9	11.2	20.3

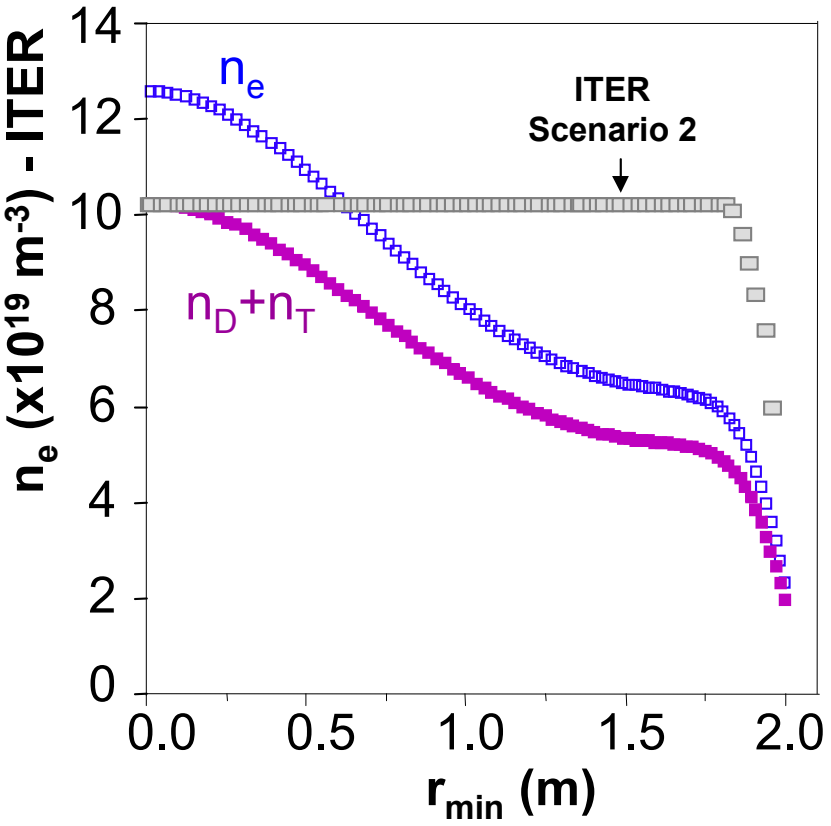
Scaling to ITER: q_{95}=3.17, β_N=2.9

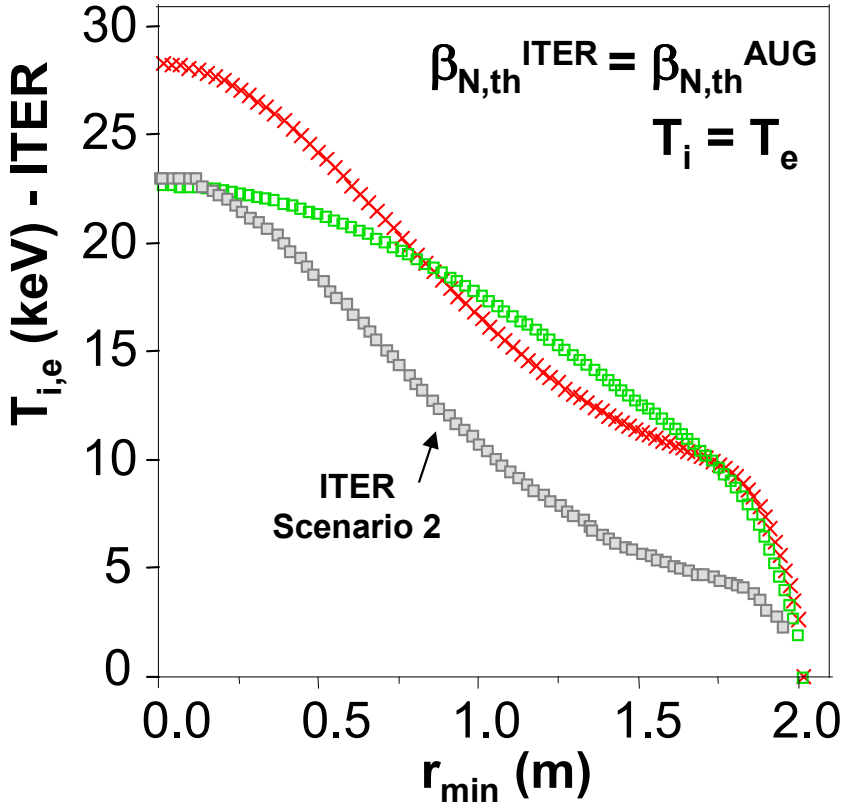




$<n_e>/n_{GW}$ =0.85	q_{95}	I_p (MA)	β_N	P_{fus} (MW)	$H_{98}(y,2)$	Q	P_{aux} (MW)	$<n_e>$ (10^{19}m^{-3})	n_{e0} (10^{19}m^{-3})	T_{e0}/T_{i0} (keV)
AUG #20449	3.17	14.2	2.87	1070	1.40	∞	0	9.6	12.2	29.5

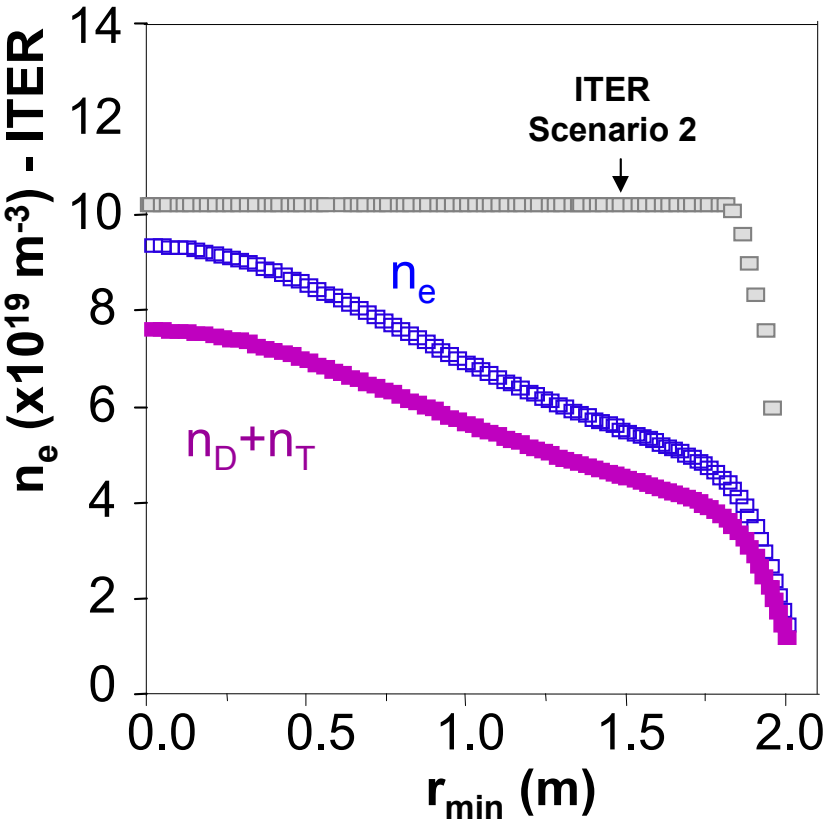
Scaling to ITER: q_{95}=3.8, β_N=2.6

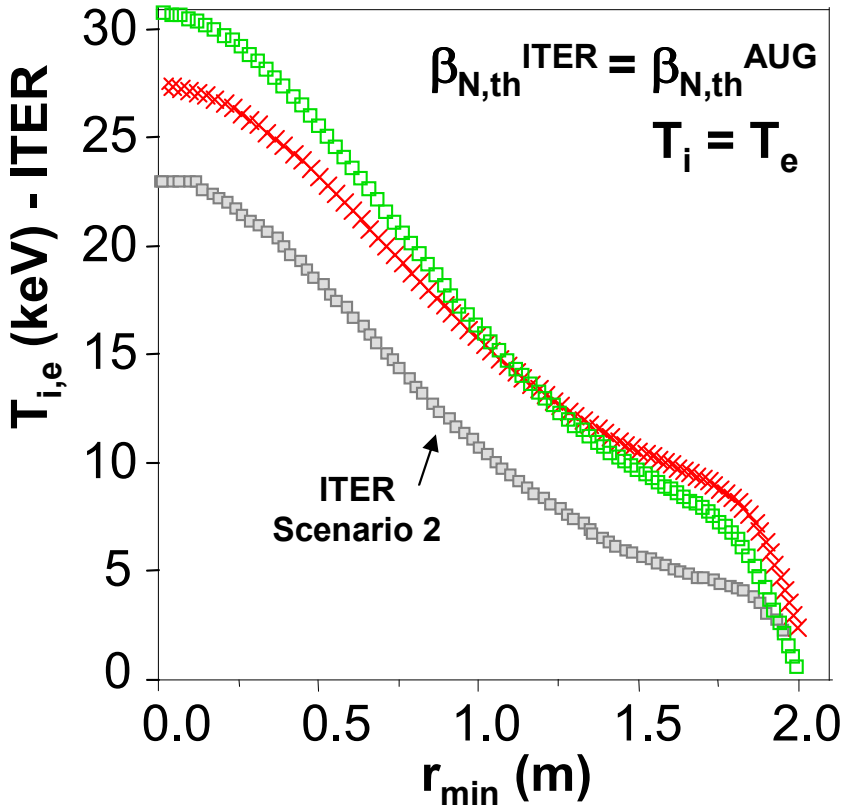




$<n_e>/n_{GW}$ =0.85	q_{95}	I_p (MA)	β_N	P_{fus} (MW)	$H_{98}(y,2)$	Q	P_{aux} (MW)	$<n_e>$ (10^{19}m^{-3})	n_{e0} (10^{19}m^{-3})	T_{e0}/T_{i0} (keV)
AUG #17870	3.8	11.8	2.63	597	1.32	11.4	52	8.0	12.6	28.2

Scaling to ITER: q_{95}=4.6, β_N=2.4



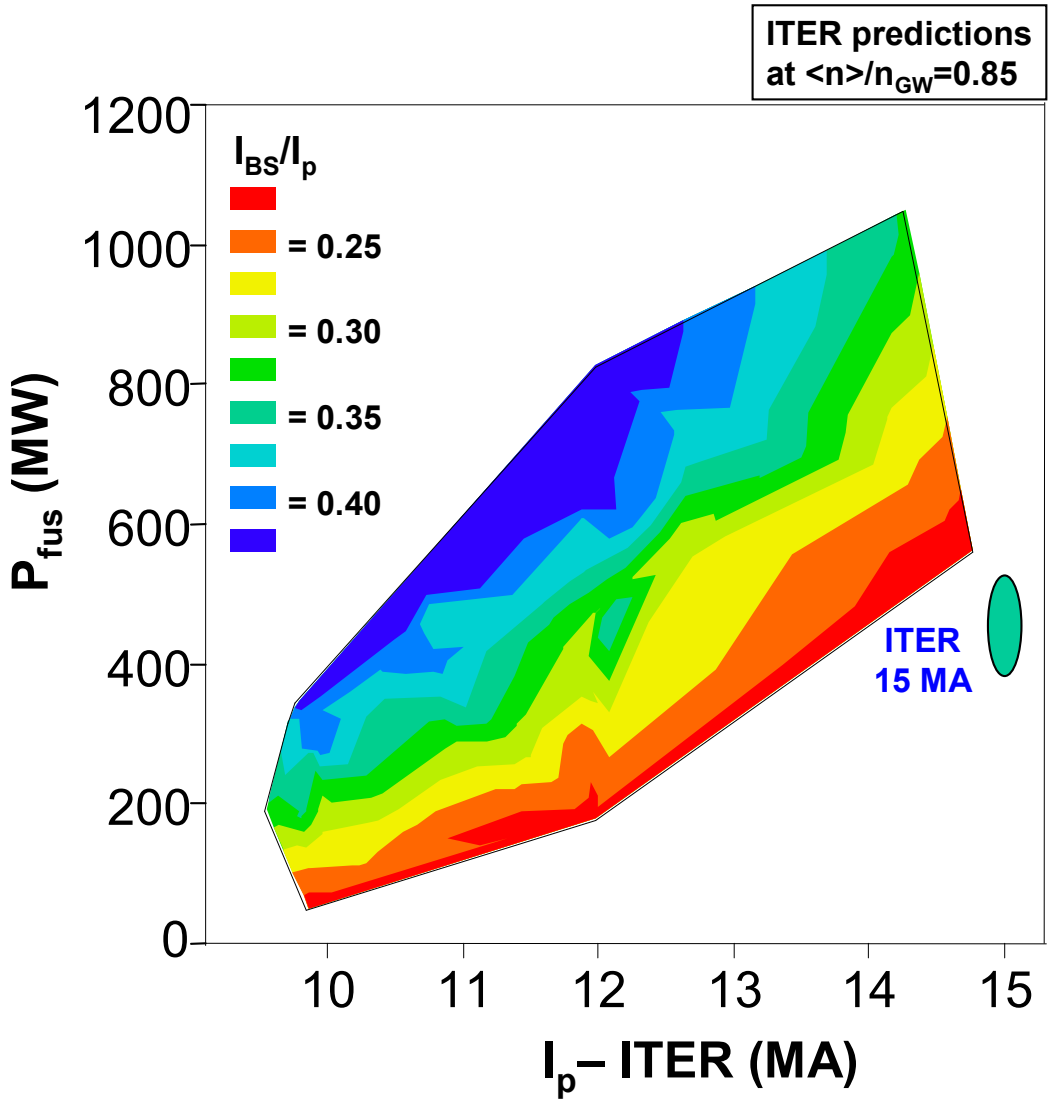


$<n_e>/n_{GW}$ =0.85	q_{95}	I_p (MA)	β_N	P_{fus} (MW)	$H_{98}(y,2)$	Q	P_{aux} (MW)	$<n_e>$ (10^{19}m^{-3})	n_{e0} (10^{19}m^{-3})	T_{e0}/T_{i0} (keV)
AUG #20448	4.6	9.7	2.41	360	1.44	6.5	55	6.6	9.4	27.4

Prediction of fusion performance in ITER

$<n_e>/n_{GW}$ =0.85	q_{95}	I_p (MA)	β_N	P_{fus} (MW)	$H_{98}(y,2)$	Q	P_{aux} (MW)	$<n_e>$ ($10^{19}m^{-3}$)	n_{e0} ($10^{19}m^{-3}$)	T_{e0}/T_{i0} (keV)
									profile shapes	
ITER Sc. 2	3.0	15.0	1.8	400	1.0	10	40	10.1	10.2	24.8/ 21.2
AUG #17847	3.05	14.7	2.10	619	0.95	8.0	(78)	9.9	11.2	20.3
AUG #20449	3.17	14.2	**2.87**	1070	1.40	∞	0	9.6	12.2	29.5
AUG #17870	**3.8**	11.8	2.63	597	1.32	11.4	52	8.0	12.6	28.2
AUG #20448	**4.6**	9.7	2.41	360	1.44	6.5	55	6.6	9.4	27.4

Prediction of fusion performance in ITER



Calculated bootstrap fraction f_{BS} increases at lower current.

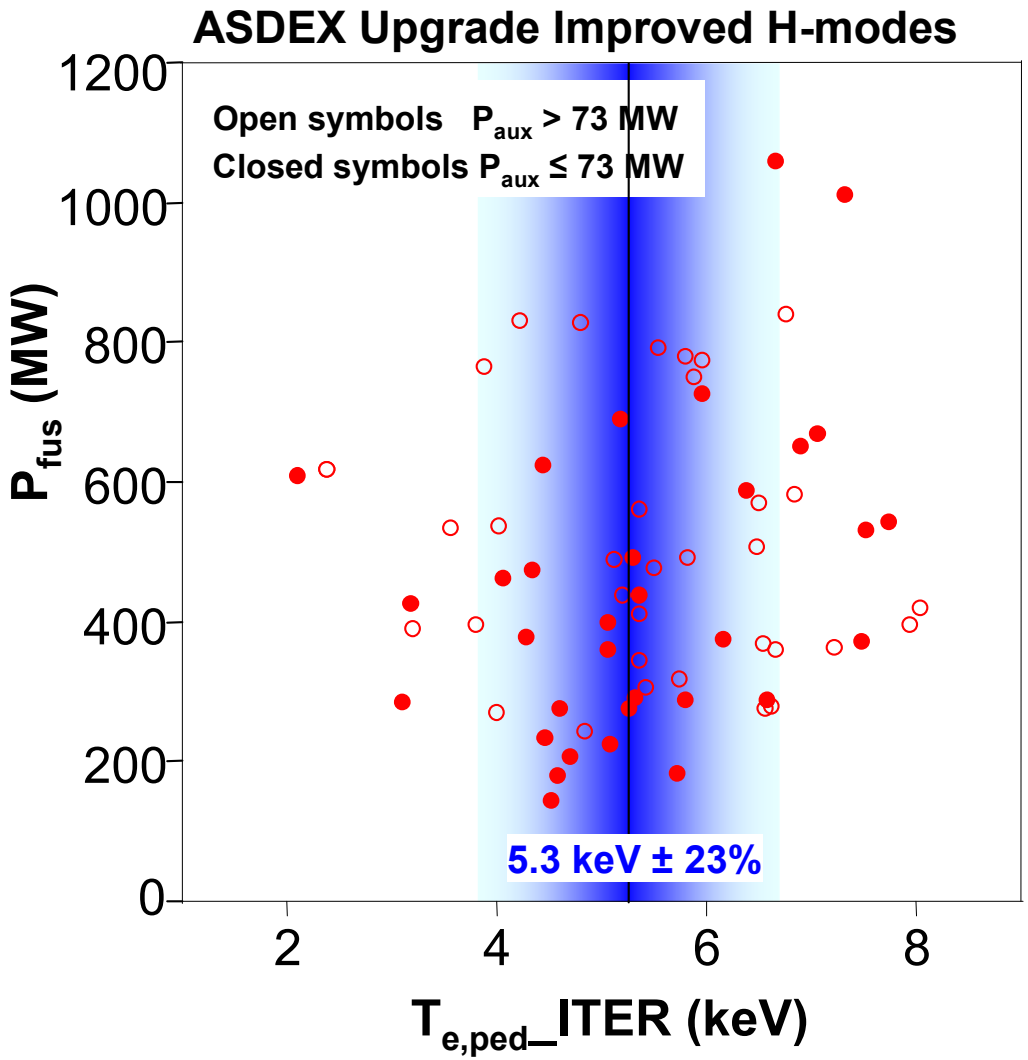
ITER (15MA) ~ 0.18.

Maximum of cases presented here: f_{BS} ~ 0.4.

A current ramp to lower plasma currents compared to reference design AND the ability to operate at same stored energy.

→ longer pulse length.

Prediction of fusion performance in ITER



Most of the scaled edge pedestal temperatures are within range of what is expected for typical H-modes in ITER.

5.3keV ± 23%

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